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POLYETHER BLOCK AMIDE: REDEFINING REALITIES ON AND OFF THE GROUND

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ABSTRACT

Polyether Block Amide (PEBAX) is a family of block copolymers with distinctive chemical, physical, and processing properties. These thermoplastic elastomers consist of rigid polyamide segments that provide physical cross-links and flexible polyether segments that act as elastic springs. This combination yields exceptional performance characteristics, most notably low-temperature flexibility. Upon its industrial introduction in 1981, this property secured PEBAX's first customer base in aerospace applications. However, PEBAX's greatest impact has been in athletics. First breaking through in the ski sector, PEBAX offered unforeseen damping and energy-return characteristics that revolutionized lightweight ski boot design. Leveraging these same advantages, Nike introduced PEBAX as ZoomX foam in its initiative to help professional athletes break the two-hour marathon barrier, highlighting its unmatched efficiency compared to conventional foams. While PEBAX remains central to high-performance sportswear, ongoing research is extending its influence to broader technological and environmental challenges, including its use in membranes capable of selectively separating carbon dioxide. This evolution, from aerospace origins to sustainable innovation, demonstrates PEBAX's enduring technological and societal relevance.

Keywords: Polyether Block Amide, PEBAX, Polymer Technology

1. HISTORY OF THE TECHNOLOGY

1.1. Motivations and Origins

The history of Polyether Block Amide (*PEBAX*) stems from the efforts of ATOCHEM, a major French chemical company, to develop non-plasticized flexible polymers. This pursuit was inspired by the limitations of conventional plasticized polymers, particularly nylon 11 and nylon 12, in which ATOCHEM was a development leader. A primary concern was the leaching of plasticizers in high-heat or harsh chemical environments, which significantly restricted the application of these materials in sensitive medical and electronic industries.

Initial research by ATOCHEM in 1974 determined that the optimal path forward lay in leveraging block copolymer technology, which was already utilized in polymers like copolyether ester elastomers and thermoplastic polyurethanes. Further investigation into non-plasticized flexible polymers identified the combination of a polyether and a polyamide as the most promising route. Although this monomer combination had been previously documented, it had not yet yielded a commercially viable thermoplastic elastomer. ATOCHEM's early synthesis attempts utilized a dicarboxylic polyamide and a polyether diol as polymer building blocks but encountered initial difficulties due to monomer incompatibility. The successful discovery of a suitable catalyst finally enabled a successful melt polycondensation reaction, which culminated in the granting of the first patents in 1974.

Subsequent development focused on identifying optimal polyethers and polyamides to establish a commercial manufacturing process. These sustained efforts resulted in a full commercial process for producing the polyether block amide, and a pilot plant was successfully introduced in 1980. In 1981, a commercial production line was launched under the tradename *PEBAX*, formally introduced at Interplas in Birmingham, England. The polymer quickly found a receptive market, leading to the establishment of a commercial *PEBAX* plant in the United States that same year [1].

1.2. Early Constraints and Characteristics

These early grades of *PEBAX* were distinguished by their low density, typically ranging from 1.00 to 1.02 g/cm^3. This intrinsic lightweight property provided a high strength-to-weight ratio, a feature that would later prove crucial for its success in the sportswear industry. Another key factor enabling the early, widespread application of *PEBAX* was its expansive range of durometer hardness, spanning Shore D 35 to 72. This range is achieved through compositional fine-tuning: higher durometer, more rigid variants contain a greater proportion of the rigid polyamide segments, while softer varieties prioritize the elastic polyether content [2]. This compositional versatility enabled *PEBAX*'s adoption across diverse industries, including the medical sector, where its predecessors nylon 11 and nylon 12 had previ-

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ously not been applicable [3]. However, this early generation of polyether block amide products was limited by their processability, as mechanical property tuning was achieved solely through chemical composition modification, lacking the ability to enhance performance via secondary processing technologies [2].

1.3. Sustainability Changes and Dynamic Performance

The first major manufacturing changes were driven by a strategic imperative to produce high-performance materials with a reduced environmental footprint. This led to the introduction of the *PEBAX Rnew* line of polymers, which replaces the original Polyamide 12 hard block with Polyamide 11, a variant that can be derived from renewable sources like castor seeds. This chemical redesign maintained key performance properties, such as the wide range of available hardnesses [4]. However, the use of Polyamide 11 accentuates certain characteristics, such as excellent impact resistance and flexibility, in contrast to the greater rigidity and dimensional stability of Polyamide 12. The advent of Polyamide 11-based *PEBAX* is particularly well-suited for dynamic applications like hinges and, critically, footwear.

The material's potential in footwear was fully realized with the later introduction of Supercritical Fluid (SCF) foaming technology. SCF techniques differentiate from traditional chemical foaming through the ability to achieve a superior microstructure, yielding an ultra-low-density foam [5]. Leveraging the combined benefits of ultra-low density and high resilience, the commercial envelope of *PEBAX* rapidly expanded into performance footwear. The SCF-enhanced *PEBAX* delivered unprecedented kinetic performance [6], with these new foams characterized by a resilience range of 85% to 87% [5].

1.4. Future Applications

Beyond its core mechanical properties, *PEBAX* maintains academic and research vitality through specialized grades. Notably, highly hydrophilic grades of *PEBAX* are employed in the creation of non-porous breathable membranes that can precisely adjust their permeation rate for water vapor and other gases [2]. These specialized membranes have opened *PEBAX* to new markets, particularly in the environmental and sustainability sectors, where their applications are being studied for separating gases, such as carbon dioxide, from other atmospheric components [7].

2. MAJOR APPLICATIONS OF PEBAX

As alluded to previously, the running footwear industry underwent dramatic change following the inclusion of *PEBAX* as the midsole material, and it is now the non-negotiable midsole material for performance shoes [8]. Under proprietary names such as Nike's *ZoomX* and Saucony's *PWRRUN PB*, *PEBAX* has enabled runners to achieve times and break barriers that were previously labeled unattainable, leading to the benefits *PEBAX* provides to be called "technological doping" [9].

Prior to *PEBAX*'s adoption into the running sphere, the polymer established a name for itself in other high-performance athletic scenarios. Specifically, as a shell for ski boots, an application facilitated by its ability to maintain key performance properties across a wide range of temperatures. *PEBAX*'s ability to withstand impact, provide energy return, and remain flexible without becoming brittle gave it a competitive edge over legacy materials. The Italian mountaineering company SCARPA first introduced *PEBAX* fabric into its *Vega* boot in the 1990s [10].

While *PEBAX*'s effect on the running industry would reach its peak with its use as a midsole foam, the polymer made its introduction to performance shoes as a rigid plate embedded in a shoe's midsole. Mizuno first utilized the material as their *Wave Plate*, which itself was situated within more traditional foams, such as EVA. The primary function of these plates was to dissipate force and increase midsole stability, a marked contrast to the energy-return maximization that plates are primarily used for today [11].

The modern era of *PEBAX*'s inclusion in performance shoes began with the breakthrough of supercritical foaming and the pursuit of a bold marketing and performance goal: achieving a sub-two-hour marathon. First formalized in 2017, Nike *unveiled* the *Breaking2* initiative with a coordinated date and setting for the event. Key to the sub-two marathon initiative was the development of new shoe technology to propel runners minutes faster than the existing world record. This process was heavily documented in Nike's *Breaking2* documentary and culminated in the predecessor "super-shoe," the *Nike Zoom VaporFly Elite*. The key aspect of the shoe is the midsole, designed to maximize energy return, which contained a *PEBAX* foam in conjunction with a full-length carbon-fiber plate. While the carbon-fiber plate received the most attention for energy return figures, newer research highlights the *PEBAX* foam as the predominant performance contributor [12]. At the event, Eliud Kipchoge crossed the line in a time of 2 hours and 25 seconds (2:00:25), and while the mark fell short of the initiative goal, the time represented a monumental leap in running ability and the technology that enables it.

FIGURE 1: Photo of the Nike Vaporfly 4%. The shoe used in the Breaking2 attempt.

Following the *Breaking2* attempt, *PEBAX* foam running shoes reached the commercial market and quickly gained the moniker of "super shoes." The performance gains enabled by these shoes were dramatic and prompted the IAAF (now World Athletics), the governing body of both track and road racing, to issue limitations on what shoes can be used in official competition [13]. These improved characteristics are primarily expressed as a percentage increase in running economy, a metric Nike used extensively and quantified at 4% [14]. While testing has confirmed increased performance, independent studies have shown less dramatic results of about a 1% increase in performance [14].

Regardless of the precise metrics of performance, *PEBAX* took a sudden and all-encompassing grip on the running landscape. Following Nike's initial introduction of the foam in 2017, every major running shoe provider has followed suit in utilizing polyether block amide, or similar competitors, as the main foam in their high-performance running shoe catalog, further solidifying the material's necessity in the running industry. Similarly to Nike, all brands have followed suit by branding *PEBAX* foams under proprietary names such as New Balance's *FuelCell* and On's *Helion HF*. In response to this, ARKEMA, the current producer of the *PEBAX* material, launched the dedicated consumer-facing initiative *PEBAX Powered*. This strategic move, post-2018, aimed to build ingredient brand awareness and create consumer demand pull, encouraging runners to actively "ask for *Pebax Powered* shoes/boots" as opposed to a particular brand of shoe [15].

3. DEVELOPMENT OF THE NIKE VAPORFLY

The success of the Nike Vaporfly can be attributed to a process of iterative refinement of the product's weight, performance, and biomechanical optimization. The conceptual beginnings of the shoe date back to 2013 through a series of prototypes collectively known as the *Mayfly*. The name derives from the insect mayfly, known for being extremely lightweight, and reflects Nike's ambition: creating an ultra-lightweight shoe [16]. Notably, this shoe did not use *PEBAX* and instead incorporated a thinned Phylon midsole to reduce weight. This compromised midsole geometry led to durability issues, as the shoe would degrade heavily after 100 miles, an unimpressive marker in the running shoe industry [17]. This precursor to the Vaporfly still has notable results in action. Most notably, it was the shoe worn by Eliud Kipchoge in the 2016 Summer Olympics marathon, an event he won.

Development of the Nike Vaporfly is heavily attributed to the aforementioned *Breaking2* initiative. In developing a shoe engineered for the marathon distance, key characteristics of the modern Vaporfly were introduced. The most prevalent of these being the uncharacteristically large stack height (33 mm) of a *PEBAX*-based foam [16]. This large stack was adopted to create more leverage with each step, increasing stride efficiency. This effect, however, was only able to be adopted due to *PEBAX*'s unique hysteresis and shock absorption characteristics. Because *PEBAX* is able to handle large shocks and return an uncharacteristically large percentage of energy, *PEBAX* technology directly enabled this development in shoe technology. When paired with other engineering breakthroughs in shoe technology, such as the Nike Vaporweave mesh and carbon fiber plates for reinforcement, Nike created trends that have been widely adopted by all brands of shoes [15]. Additionally, in more recent iterations of the Vaporfly, these characteristics, such as stack height, have increased further, showing their performance relevance.

The Vaporfly's influence on distance running is both holistic and measurable, with numerous studies supporting its role in improving running efficiency. Nike's central marketing claim for the Vaporfly is a 4% enhancement in running economy compared to other elite marathon shoes, a figure derived from postdoctoral research by Wouter Hoogkamer at the University of Colorado Boulder [19]. This improvement reflects a significant reduction in the metabolic cost of maintaining marathon pace, translating into meaningful time savings over long distances.

Model	Release Year	Stack Height	Drop (mm)
Vaporfly 4%	2017	~33 mm	11
Vaporfly NEXT%	2019	~40 mm	8
Vaporfly NEXT% 4	2025	~40 mm	8

TABLE 1: Nike Vaporfly Model Evolution: Stack Height and Drop [18]

As other brands quickly adopted similar design principles, including advanced foams and carbon plates, the performance gap between shoes narrowed. A more recent study by Hoogkamer found only a 1.5% difference in running economy among shoes from various manufacturers that use *PEBAX*-based foams [20], highlighting how the market has become saturated with high-efficiency footwear.

4. OVERVIEW OF PEBAX TECHNOLOGY

PEBAX functions as a thermoplastic elastomer, possessing properties of elastomers through physical cross-linking between chains while also possessing typical thermoplastic properties such as melt processing [21]. Polyether block amide is a copolymer, containing segments of both polyamide and polyether. The polyamide segments, typically derived from Nylon 11 (PA11) or Nylon 12 (PA12), provide *PEBAX* with properties typically relating to strength, such as impact strength and durability. These segments, often referred to as the *hard block*, prevent large-scale chain slipping of the polymer under stresses at room temperature [21]. Conversely, the polyether segment, often sourced from polyethylene oxide, is the primary source for *PEBAX*'s elasticity, flexibility, and performance at low temperatures. These polyether segments have been a key area of interest lately, as they are the primary gateway for gas transport in *PEBAX*'s membrane applications [22]. Figure 2. displays the chemical structure of PEBAX 1657, which includes PA6 as a hard block and polyethylene-oxide (PEO).

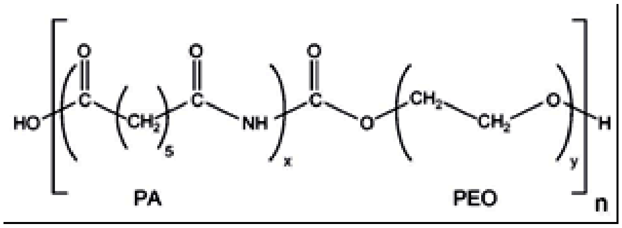

FIGURE 2: Chemical Structure of PEBAX 1657

Being a copolymer, *PEBAX* benefits from the same mechanical fine-tuning that results from changing copolymer composition. This method effectively removes the need for additional fillers, such as plasticizers, and the issues relating to their degradation [21]. Changing the percent content of polyamide to polyether also affects macroscopic material properties. Notably, increasing the polyamide content results in a semi-crystalline matrix characteristic of nylons and yields high stiffness, toughness, and Young's modulus. The opposite can be said for increasing polyether content, as that results in an amorphous matrix and a more flexible polymer [22].

Within each component, the hard block and the soft block, polymer substitution can result in major macroscopic mechanical changes. As referenced earlier, the *PEBAX Rnew* line of polymers substituted polyamide 11 for polyamide 12, resulting in noticeable property changes. Polyamide 11 offers better UV stability and exhibits higher elasticity than Polyamide 12 [23]. In contrast, polyamide 12 offers better strength characteristics and an ability to maintain performance at elevated temperatures. These properties, in addition to its superior chemical resistance to oils, solvents, and hydraulic fluids, make polyamide 12 a more useful component for *PEBAX* in typical engineering applications [23].

The synthesis of *PEBAX* (polyether-block-amide, PEBA) is typically achieved through a melt polycondensation reaction between an acid-terminated polyamide block and a hydroxyl-terminated polyether block. This process is carried out under high vacuum at elevated temperatures, often around 250°C, to promote chain growth and remove condensation by-products such as water. A titanium alkoxide catalyst, commonly of the form $\mathrm{Ti(OR)_4}$, is employed to facilitate the coupling reaction and achieve high molecular weight. The resulting segmented block copolymer comprises rigid polyamide domains and flexible polyether segments. In the solid state, the crystalline polyamide blocks form hard domains that act as reversible physical cross-links, imparting strength and thermal stability, while the amorphous polyether segments provide elasticity and energy dissipation. The balance between these two phases governs the overall mechanical performance of the material [3].

The performance of *PEBAX* and the precise properties it can achieve depend heavily on processing techniques. The most significant of these, which enabled *PEBAX* to enter the sportswear industry, is supercritical foaming (SCF). This process enabled *PEBAX*'s tight hysteresis curve—reflecting its rapid stress response—and its high energy return to help runners achieve faster times [15]. SCF relies on non-toxic agents, such as supercritical carbon dioxide, to saturate the amorphous, and thus permeable, polyether segments under high pressure. Under a controlled depressurization process, the supercritical carbon dioxide acts as a nucleation agent, leading to the formation of an extremely low-density and uniform microstructure. This structure not only reduces weight but also enables even energy return through its uniform nature [8].

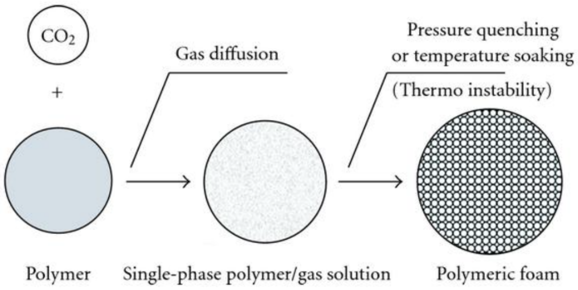

FIGURE 3: Process flow diagram of Supercritical Foaming

Recent environmental applications of *PEBAX* utilize its membrane for the separation of gases, primarily carbon dioxide, in an effort to reduce carbon emissions. Gas separation utilizing *PEBAX* membranes is modeled by the separation-diffusion model, where gas permeability (P) is related to thermodynamic (gas solubility coefficient) and kinetic (gas diffusion coefficient) properties. Materials possessing good gas permeability must possess desirable solubility or diffusion characteristics. *PEBAX* in particular contains desirable solubility characteristics as a result of the amorphous polyether segments, which interact strongly with polarizable gases, or gases that can exhibit a dipole when in the presence of an electric field, such as carbon dioxide. As such, useful variants of *PEBAX* for gas separation purposes contain large polyether components [24].

5. FINANCIAL CONSIDERATIONS

PEBAX's use in performance footwear and other specialty applications typically comes with a high price associated with high-performance plastics. Therefore, the use of *PEBAX* has to be justified relative to its performance. Traditional polymers used in the midsole of shoes, such as EVA, serve as the industry standard for pricing and performance. While at a notably lower price range (~ $1.89 per kg), EVA shows diminished performance in key attributes such as energy return, typically around 60–65%, far less than *PEBAX*-based foams, which provide beyond 80% return. Additionally, EVA is susceptible to temperature-based property changes [25]. Therefore, the premium paid for *PEBAX*-based foams is a product of their increased performance, something that is unparalleled and non-negotiable for most athletes. This justifies its price, which climbs above ~ $20 per kg. Additionally, production methods for these foams, SCF in partic-

Property	**PEBAX (Polyether Block Amide)**	**TPU (Thermoplastic Polyurethane)**	**EVA (Ethylene-Vinyl Acetate)**
Energy Return (Resilience)	~ 87% resilience [6]	40%−52% resilience [6]	40% − 52% resilience [6]
Energy Loss (Hysteresis)	Extremely low (High efficiency) [9]	Higher loss [9]	Higher loss [9]
Weight / Density	Typically 20% lighter than competitive polymers [2, 21]	Standard density (Heavier) [2]	Standard density (Heavier) [2]
Cold Temperature Performance	Insensitive to temperature change [2, 23]	Insensitive to temperature change [23]	Sensitive to temperature changes [25]

TABLE 2: Comparative performance metrics for PEBAX elastomers against common midsole polymers.

ular, come with hefty price tags that further increase the cost of *PEBAX*-based foams. Supercritical Fluid Extraction (SFE) is a pivotal step in obtaining the supercritical fluid used to saturate *PEBAX*'s polyether segments, allowing them to be turned into foams. Production-scale units for SFE can regularly exceed $1 million, accentuating *PEBAX*'s dependence on price. The justification for deploying multi-million dollar industrial SFE systems is derived not from cost reduction in the traditional sense, but from the ability to achieve performance-critical material structures, such as optimized cell morphology in *PEBAX* foams, and to maintain continuous, highly efficient production yields unattainable by smaller or conventional units [26].

Market trends, however, indicate that the price disparity, especially for *PEBAX*-based foams, is diminishing as the technology continues to advance. Traditionally only reserved for high-end performance shoes, like what was seen in Nike's *Breaking2* campaign, *PEBAX* foams have slowly seeped into running shoes with less emphasis on performance and a lower price tag, indicating a decreased dependence of cost on these systems [25]. This is aided by ARKEMA's recent increase of *PEBAX* production by 40%, which supports price reduction [27]. Beyond this, the introduction of high-performance polymers to the running shoe market has shifted priorities in shoe purchasing, as consumers now prioritize performance over cost in many cases.

The adoption of green initiatives for the sourcing and production of materials can drive up the cost of the end product, as green production often comes with sourcing materials from a more expensive medium and relying on production technologies that are less efficient than traditionally used methods. This culminates in a so-called *green premium* associated with environmentally sustainable products and is applicable to green *PEBAX*-based lines such as *PEBAX Rnew* [27]. On average, extracting polyamide 11 from castor beans comes with a 30% increase in price compared to petroleum-based polyamide 12. However, while sourcing for polyamide 11 comes with an increased price tag, a difference in properties, such as increased ductility and elasticity when compared to polyamide 12, increases ease of production and offsets some of the cost of sourcing, allowing for green sourcing of *PEBAX Rnew* with minimal price increases [28].

PEBAX's integration into carbon dioxide capture presents an economically viable alternative to traditional gas capture technology such as amine absorption. Membrane systems, like the *PEBAX* systems currently being studied, have characteristically moderate prices and substantially lower operation costs, as they remove additional operational steps that drive cost. Additionally, membrane systems lend themselves to better scalability than traditional chemical absorption processes [22]. However, this financial feasibility is dependent on membrane production cost and gas absorption performance. Membrane analysis assumes a manufacturing price of $50 per m^2; with this price taken into consideration, the membrane system must achieve a permeance of 2,250 GPU (Gas Permeance Unit) to compete with traditional chemical absorption technology. Membrane-driven systems do not yet achieve permeance of this magnitude, and as such, current R&D efforts are focused on bolstering permeance for industrial viability [29].

6. FUTURE OF PEBAX TECHNOLOGY

PEBAX's use has extended far beyond the athletics and gas separation industries. One sector that has seen extensive *PEBAX* application is the medical industry. Despite the profound impact the polymer has already had on medical devices, further adoption is inevitable as material development progresses. The future of *PEBAX* in the medical field is multi-faceted, extending beyond its inherent properties. Notably, the medical industry is heavily constrained by regulations—a domain in which *PEBAX* is well-positioned for growth. Medical grades of *PEBAX*, such as *PEBAX MED*, offer strategic advantages through compliance with key standards like USP Class VI and FDA regulations [30]. *PEBAX MED* polymers have already secured a role in medical care devices, particularly angioplasty catheters. Used by cardiovascular surgeons, *PEBAX*'s combination of strength, flexibility, and low surface friction allows for smooth navigation through cardiovascular pathways [30]. Beyond this, *PEBAX* is being considered for a critical role in drug-eluting stents—devices that enable controlled, prolonged drug release. The effectiveness of these systems depends on the stability of the coating on the device surface. Research confirms *PEBAX*'s suitability for this application, as the polyamide 12 segments found in *PEBAX 1074* orient well with the balloon surfaces used in these devices, ensuring proper coating adhesion [31].

While *PEBAX* has demonstrated its versatility in medical applications, its potential in additive manufacturing (AM) represents one of its most promising future directions. As AM technologies continue to advance, the demand for materials that combine mechanical performance, processability, and sustainability is growing. *PEBAX* is uniquely positioned to meet these needs. Recent developments have shown that the *PEBAX Rnew* line, in particular, is well-suited for fused filament fabrication (FFF), a widely used AM technique [32]. Two grades—*PEBAX Rnew 35R53* and *PEBAX Rnew 1100*—have been successfully extruded into filaments and used in FFF printing [33]. *PEBAX Rnew 35R53*, with a Shore hardness of 25D, is among the softest printable materials available, making it ideal for flexible components. In contrast, *PEBAX Rnew 1100* offers significantly higher rigidity, enabling structural applications [34]. The adhesion between these two grades has also been studied, revealing promising results for multi-material printing, where regions of varying stiffness are required within a single part.

Additionally, thermal analysis via differential scanning calorimetry (DSC) and thermo-gravimetric analysis (TGA) confirms that both grades possess suitable thermal stability for AM processes. *PEBAX Rnew 35R53* exhibits a melting temperature around 135°C and a glass transition near −23°C, while *PEBAX Rnew 1100* melts at approximately 188°C, reflecting its higher polyamide content [34]. These properties ensure compatibility with standard FFF equipment and allow for reliable layer adhesion and dimensional stability during printing. Rheological studies further support *PEBAX*'s suitability for AM. Both grades display shear-thinning behavior, which facilitates smooth extrusion through printer nozzles. Compared to conventional thermoplastic polyurethanes (TPUs), *PEBAX* shows reduced viscosity variation under shear, contributing to improved process stability and print quality [34].

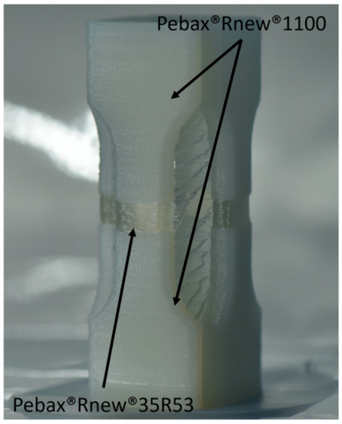

FIGURE 4: Fused filament fabrication of PEBAX Rnew 1100 and Pebax Rnew 35R53 [34]

The growing interest in bio-based polymers also aligns with broader sustainability goals in manufacturing. *PEBAX*'s renewable origin and recyclability make it a compelling choice for industries seeking to reduce their environmental footprint. As AM expands into sectors such as biomedical devices, wearables, and soft robotics, *PEBAX* offers a material platform that combines performance, adaptability, and eco-consciousness.

7. ENVIRONMENTAL AND SOCIAL CONSIDERATIONS

The creation of the *PEBAX Rnew* line of polymers is a byproduct of shifting global priorities towards greener material alternatives. This line serves as both a sustainable sourcing technique and a use case for the non-edible castor plant [35]. By utilizing the castor plant, the sourcing of the Rnew line avoids competition with the food supply chain and takes advantage of a crop that requires minimal water to grow, thereby addressing concerns about land and water usage for other activities [35]. The success of the Rnew line is predicated on its uncompromised mechanical performance despite unconventional sourcing. This defies historical trends, as other bio-based polymers, such as PLA and bio-PE, are characterized by diminished mechanical properties resulting from sustainable sourcing practices [36]. Environmental benefits for the Rnew line extend beyond the sourcing of the polymer: *PEBAX*'s lightweight nature as a whole yields secondary carbon benefits, such as decreased energy expenditure for products that use *PEBAX* in place of other heavier materials [35].

An assessment of *PEBAX Rnew*'s environmental profile was formalized through the completion of a Life Cycle Assessment (LCA) and processes consistent with ISO 14040, 14044, and 14067 standards. In this process, the manufacturer evaluates the cradle-to-gate environmental impact of their product, which encompasses all facets of the product's creation, including sourcing, manufacturing, and distribution [35]. A factor that delineates the Rnew line from other bio-based polymers is that production of the main building block, polyamide 11, is completely bio-based. This removes ambiguity about sourcing, as other biopolymers rely on theoretical calculations for the amount of sustainable content used in the production of the polymer [35]. The LCA also compares Rnew to other thermoplastic elastomers and shows a 29% reduction in fossil energy used and a 32% reduction of carbon emissions [37].

ARKEMA, the manufacturer of *PEBAX*, has leveraged this sustainability as a driver to increase production of *PEBAX*. A significant investment was made to increase the global production of all *PEBAX* products by 25% at the Serquigny plant in France. This investment, which came online mid-2023, is linked to resource efficiency, as it included a 25% decrease in water consumption for the Serquigny plant [27]. ARKEMA has incorporated the REED environmental reporting system to bolster internal accountability. This system creates and tracks compliance of Environmental Footprint Performance Indicators (EFPIs) and consistently evaluates company compliance internally for all EFPIs [38]. Table 3 shows the EFPIs ARKEMA tracked for in 2021.

Impact Category	**Conventional PEBAX (PA12 Block, Fossil-based)**	**PEBAX Rnew (PA11 Block, Bio-based)**	**Source Data Scope**
Fossil Energy Consumption	Baseline	Up to 29% Reduction	LCA (Cradle-to-Gate)
Equivalent CO_2 Emissions	Baseline	Up to 32% Reduction	LCA (Cradle-to-Gate)
PA11 Carbon Footprint	N/A	1.3 kg CO_2/unit	Global Production, 100% Segregated Bio-Based
Serquigny Water Consumption	Baseline (Pre-2023)	25% Reduction Goal (Post-Investment)	Operational Process Optimization

TABLE 3: Comparison of environmental impact between conventional and bio-based PEBAX.

The production of bio-based polymers carries the social responsibility of ethically sourcing the critical materials. The non-edible nature of the crop removes food-chain considerations, but careful consideration must still be made toward the workers who source the crop. ARKEMA explicitly ensures the ethical integrity of the sourcing process. This commitment includes ensuring "no compromise on ethics or environmental impacts such as deforestation, food competition, ethical labor conditions, fair trading" [35]. This commitment is further cemented by the Pragati program, a collaborative project that operates primarily in Gujarat, India, the source region for the majority of the world's castor supply. The Pragati project is structured around specific pillars designed to address both socio-economic welfare and environmental stewardship at the agricultural level, as seen below [39].

1. **Economic Viability:** Promoting Good Agricultural Practices (GAP) to enhance crop yield and, consequently, increase farmer income.

2. **Environmental Stewardship:** Enabling efficient water resource utilization and actively working to maintain soil fertility. The inherently low water requirement of the castor plant is further optimized through GAP.

3. **Human Rights and Safety:** Ensuring the implementation of better health and safety practices and explicit respect for human rights within the labor force.

4. **Operational Environment:** Driving the adoption of responsible waste management practices on farms.

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