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Polypropylene biocomposites reinforced with softwood, *abaca*, jute, and kenaf fibers

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ABSTRACT

The presented research study compares different types of common natural fibers used as a reinforcement in plastic composite industry. It contains characterization of each fiber type, its preparation method, and its chemical and physical properties. It follows from a description of the polypropylene biocomposite manufacturing process and physical properties of the obtained biocomposite materials. The biocomposites were manufactured in the same way and have the same matrix-to-fibre content (60/40 wt%). Therefore, the particular physical and chemical properties of the fibers used as a reinforcement and their influence onto mechanical properties of their biocomposites can be evaluated. This approach provides practical tools of how to tailor the properties of PP biocomposites by simply choosing an adequate fiber type as a matrix reinforcement. Furthermore, the information regarding: cultivation, price, and availability are compared to give a holistic view for these most common natural fibers for technical applications in plastic industry.

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1. Introduction

Natural fibers of vegetable origin have been used as a reinforcement in plastic resins and thermoplastics since the very beginning of this branch of chemical industry. Thermosetting composites reinforced with cellulose fibers were introduced to the automotive industry by Ford and DKW in the 1920s of the last century. Natural fibers were later on surpassed by synthetic fibers on account of their competitive price, production output, and higher performance (Bledzki et al., 2012). Although synthetic fibers excel in these terms, natural ones have still some unique properties, which may benefit their composites in some applications. Their most important advantages are lower density, vibration dumping, and blunt fracture. The resistance to creep under load in elevated temperatures can be increased to the same extent as with synthetic fibers. They reduce also wear of screws and barrels of plastic processing equipment compared with commonly used glass fibers. Another issue which turns back attention of the plastic industry toward natural fibers is the trend toward the application of raw-renewable resources and concerns on reduction of greenhouse gases and CO_2 emissions. Besides more favorable eco-balance, than their synthetic counterparts, natural fibers as raw-renewable materials may help to diversify raw resources and are independent from the price of crude oil. Furthermore, at the end of their life, they can be burned as a fuel without emitting greenhouse gases (Faruk et al., 2012; Bledzki and Gassan, 1999; Beier, 2009).

Natural fibers can be produced from different parts of plants like leafs, bast, stem, bark, or seeds. This process involves harvesting, soaking, brushing, and drying. Their chemical composition, especially cellulose content and the orientation of fibrils determines mechanical properties of each fiber type. All natural fibers for industrial applications have high amounts of cellulose, but the structure of cellulose microfibrils may vary, resulting in different tensile strengths and elongations at stress. Also the diameter of a single fiber is different for each fiber type. The main natural fibers applied in the plastic industry are: jute, *sisal*, flax, coir, *abaca*, kenaf, and softwood (Faruk et al., 2012; FAO, 2014).

Natural fibers consist of polar lignocellulosic matter, therefore, in case of the reinforcing process of non-polar polyolefine matrices a coupling agent has to be used. Commonly used anhydride grafted polyolefine waxes provide a solution, that can be readily applied during plastic processing as compatibilizers. This is advantageous compared to synthetic fibers, on which an additional seizing must be applied at the stage of fiber production in order

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to create interphase between matrix and fiber. The polarity of lignocellulose results in hydrophobic nature of natural fibers, so the drying before processing is essential in order to avoid weakening of fiber-matrix interface due to vaporizing of water from fiber at elevated processing temperatures. Attention must be paid also to keep the processing at possibly low temperatures (200 °C), to avoid decomposition of lignin, which may result in deterioration of fibers' strength. For these reasons, polypropylene is most likely to be used as an engineering plastic for the manufacture of natural fiber biocomposites (Faruk et al., 2012; Bledzki and Gassan, 1999).

This paper presents biocomposites reinforced with the most popular industrial grade natural fibers used in technical applications. They contain equal fiber to matrix weight ratios, compatibilizer content and were manufactured and processed in exactly the same way. This approach enables to give a better insight into how the physical properties of fibers and their geometry influence the mechanical properties of their composites. This gives a far more accurate estimation than mostly provided collations of data from different overview articles and handbooks.

1.1. Softwood

Wood fibers are divided into two main categories – softwood and hardwood (fibers derived from respectively – soft conifers and hard deciduous trees). Softwood is the common name given to conifers, classified botanically as Gymnosperms, which means that their seeds are not enclosed in the ovary of the flower. The main difference in the anatomy of soft and hardwoods is lack of pores in softwood species. Softwoods have usually bearing in cone form plants with needle or scale-like evergreen leaves. In comparison to hardwoods, softwoods represent a smaller percentage of the diversity seen in the structure and morphology. Beyond that softwoods have a simpler structure than hardwoods, because it consists of only two types of cell which exhibits little variation. The basic structural elements of softwood are longitudinal tracheids – long and slender cells (90%), besides this – transversely oriented ray parenchyma (10%). The arrangement of tracheids is ordered, they are placed in neat rows within the trunk. Longitudinal elements are responsible for all structural support and conduction. The ray parenchyma ensures conduction and storage in the transverse direction. Common species of softwoods used in wood–plastic include pine, spruce, and fir. For the purposes of wood–plastic composite production the wood flour or very short fibers are used. In most cases, these can be obtained directly from forest product companies, such as sawmills, limber mills as a byproduct of wood processing. One exception from the rule is the automotive industry where also long fibers from softwood are used at compression molding of thermoplastic composites (Bledzki et al., 2002, 2006; Green et al., 1999; Östman, 1985; Mohanty et al., 2005; Shmulsky and Jones, 2011).

1.2. Abaca

Abaca is extracted from the leaf sheath around the trunk of the *abaca* plant (*Musa textilis*), which is a species of banana tree native to the Philippines. Presently, banana fiber is a waste product of banana cultivation. Therefore, the manufacturing of fibers for industrial purposes is possible at the cost of their processing. The world's leading *abaca* fiber producer is the Philippines (57,000 t in 2010), and the second – Ecuador (10,000 t in 2010).

A single fiber has a length up to 3 m. *Abaca* fiber exhibits great mechanical strength (it is considered the strongest among natural fibers) and resistance to saltwater damage and is lustrous and light beige in color. Even in comparison to its synthetic counterparts (like nylon), *abaca* fiber has higher tensile strength and lower elongation.

Abaca is still used in the production of ropes, twines, fishing lines, and nets, as well as coarse cloth for sacking. It is also used for *abaca* clothing, curtains, screens, and furnishing. However, most of fibers are processed into specialty paper e.g., for tea and coffee bags, sausage casing paper, currency notes, cigaret filter papers, vacuum bags, and more. In some applications in automotive industry *abaca* fibers have a potential to substitute glass fibers. They have been used for many years by Daimler–Chrysler in the production of interior and exterior car parts (FAO, 2014; Bledzki et al., 2006; Koronis et al., 2013).

1.3. Jute

Jute is the most important plant alongside with cotton that are cultivated solely for their fibers. Jute fibers are extracted from the bark of the white jute plant (*Corchorus capsularis*) and from tossa jute (*C. olitorius*) by either biological or chemical retting process. It is characterized by golden and silky shine and therefore, known as 'the Golden Fiber'. A single jute fiber has a length ranging from 1 to 4 m. Jute fibers consist mostly of cellulose and lignin. The structure of a jute fiber has a polygonal section of various sizes, which results in uneven thickness of fiber cell walls, and this in turn causes variations in strength.

Jute bast fiber is separated from the pith in a retting process. In case of water retting, cut jute stalks are placed in ponds for several weeks. Microbial action in the pond softens the jute fiber and weakens the bonds between the individual fibers and the pith. The fiber strands are then manually stripped from the jute stick and hung on racks to dry.

Jute fibre is a good insulator and it has antistatic properties. Moreover, it is characterized by moderate moisture retention. It is resistant to microorganisms, but not to chemical and photochemical attack. Due to a high lignin content (up to 20%), jute fibers are brittle, but strong and have a low extension to break (about 1.5%). Jute fibers are used in many sectors of industry, like fashion, travel, luggage, furnishing and in the production of carpets and other floor coverings, and last but not least as a reinforcement in biocomposites (FAO, 2014; Mohanty et al., 2005; Koronis et al., 2013).

1.4. Kenaf

Kenaf, known also as *Hibiscus cannabinus* is a plant in the genus *Hibiscus* and has about 300 species. It is a warm season annual fiber crop of the Malvaceae family, which is known for its economic importance and it is closely related to cotton and okra. It originated from Africa, but nowadays it is planted in many parts of the world owing to its low growing requirements. It reaches heights up to 2.4 to 6 m in 5 months. This plant is distinguished by highest carbon dioxide absorption among other plants (1 t of kenaf absorbs 1.5 t of atmospheric carbon dioxide).

The fibers in kenaf are situated in the bast (cortical layer) and core (wood). The bast constitutes 40% of the plant. The single fibers are 2–6 m long. Kenaf fibers are usually extracted using the same method as in jute. However, environmental concerns prevent the retting of kenaf fiber in some countries, therefore, alternative means of separating the bast from the pith are employed. In dry separation, which fractures the pith, the kenaf stalk is chopped into shorter lengths. Subsequently standard screening and air separation techniques can be used to separate the two different materials. Commercially, kenaf bast fiber separated this way can be purchased 98% pith-free.

Kenaf fiber has a pale color because it contains less noncellulosic compounds than e.g., jute. Its fibers are coarse and quite brittle. It exhibits breaking strength similar to jute (Bledzki et al., 2002; Mohanty et al., 2005; Koronis et al., 2013).

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