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Processing and properties of sorghum stem fragment-polyethylene composites

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ABSTRACT

Composites prepared with whole sorghum stem fragments reinforcing a polyethylene matrix were studied using ten different sorghum genotypes. Using a robust processing protocol, it is shown that for a given sorghum genotype, the composition of the stem fragments varies depending on the size of the sieved fragments but with the genotype effect being larger than the sieving effect. There is a variation of mechanical properties between the genotypes (from 0.6 to 1 GPa for modulus, from 7.2 to 11.5 MPa for tensile strength and from 4.4 to 6.2 kJ/m2 for impact strength). The genotypes giving the best tensile mechanical properties are the ones which have the highest viscosity, which show during blending the largest energy dissipation and which have the less decrease of size after processing. There is a weak correlation between tensile mechanical properties and resistance to impact suggesting that it is not the same tissues or physical properties which contribute to these two tests.

1. Introduction

Sorghum is a low input and multi-purpose crop which has traditionally been used in two main sectors: either directly as food for human being and feed in Africa and Asia or mainly as animal feeds in the developed countries and in Latin America. High environmental adaptation, high productivity and tolerance to salt and drought are among the properties of sorghum. This gives characteristics which are of great interests in the view of a possible climate change in Europe. Because sorghum stems are rich in soluble sugars (i.e. glucose, sucrose and fructose) and insoluble carbohydrates (i.e. cellulose and hemicellulose), they have been considered as energy crop parts for producing biofuels, bioenergy, biogas and bioethanol (Almodares and Hadi, 2009; Matsakas and Christakopoulos, 2013; Nikzad et al., 2014; Ostovareh et al., 2015). A few value-added products have been investigated like cellulose pulp for the production of paper (Albert et al., 2011; Belayachi and Delmas, 1995; Gençer and Şahin, 2015; Khristova and Gabir, 1990), particleboard (Khazaeian et al., 2015), chemicals and other bio-products (Dong et al., 2013; Tanamool et al., 2013), SiC nanoscale particles and nanorods from burned leaves (Qadri et al., 2013) and reinforcement for fly ash-based geopolymer (Chen et al., 2013). However, the sorghum stalks/stems have not yet been thoroughly investigated as a renewable natural resource for non-food applications.

Very few studies reported the use of sorghum stems in polymer composites. Thermoplastic composite panels were prepared with high-density polyethylene (HDPE) by hot-pressing layers of sorghum stalks and HDPE films (Qi et al., 2013). Poly(L-lactide) composites reinforced with sweet sorghum fiber residue obtained after sugar extraction of sorghum stalks were studied (Zhong et al., 2010). However, regarding the qualities of sorghum, it is worth investigating the possibility to use stem fragments to reinforce polymers. It is the first objective of the research reported here. It has to be said that the whole plant stem is broken into elongated pieces (called fragments in this paper) of dimensions inferior to millimeters by mechanical means (i.e. cutting and milling or grinding). No isolated fibers are extracted from the sorghum stems. The second objective is to select appropriate processing conditions in a protocol which is able to highlight the influence of the filler on the mechanical properties of the composite. It aims to study the relationships between genotype characteristics and composite properties, since sorghum genotypes present a large chemical composition

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variability. Contrary to most plant fillers which consist of extracted fibers with a high cellulose content, the use of biomass fragments obtained by grinding whole stems is posing additional challenges, but offers the opportunity to avoid chemical treatments and to decrease cost. How the biochemical composition of the plant stem or its histological structure are influencing the breaking of the stem, its mechanical resistance, and the type of tissues exposed at the stem fragment surface, for example, is unknown. Such aspects are critical since they will control the final properties of the composite.

There have been numerous published works dealing with the understanding the influence of the structure of plant parts able to be used in non-food applications on final properties, as for example for flax, a fiber used for reinforcing polymers (Bourmaud et al., 2013; Thuault et al., 2015). When using plants to reinforce polymers, the situation is complicated by the fact that in most cases, the reinforcing material (i.e. fibers) are extracted from the plant, as in the case of flax, hemp or curauá. These extracted materials are mostly composed of cellulose, not representative of the whole plant stem. There is currently no data on the relation between the whole plant properties and the properties of composites prepared with these plants considering different genotypes from one given plant species. One of the reasons could be the difficulty to prepare in a very robust manner composites using small amount of plant materials. To the best of our knowledge, aside a similar work on miscanthus from our teams (Girones et al., 2016), there is no information about the direct relationship between the histological structure and biochemical composition of the whole stem plant and the mechanical properties of the manufactured polymer composites, considering only one plant species and its various genotypes. This article is a step towards this goal.

After removing grains, leaves and leaf sheaths, dried sorghum stems from ten different genotypes were milled in controlled and reproducible conditions to produce elongated stem fragments. Fragments with controlled size distribution were selected by sieving and used to prepare composites. A robust method for preparing composites and testing their mechanical properties was devised in order to ensure that any change in the mechanical performance of a composite prepared with a given composite was only due to the influence of the variability of the sorghum stem fragments.

2. Materials and method

2.1. Preparation of reinforcement stem fragments

First, 396 sorghum genotypes were screened for their stem biochemical composition and ten genotypes were selected in order to maximize the coverage of the variability of stem biochemical properties.

These ten genotypes of sorghum were harvested and dried in October 2013 by Eurosorgho (France), which provided stem sections from 30 cm to 1 m length. Some of their stem phenotypic characteristics are presented in Table 1. The heritabilities of the different components of the biomass are quite high, underlying the fact that the differences observed between genotypes are quite stable even when they are exposed to different environmental conditions (Trouche et al., 2014). After reception, the stems were stored in a closed shelter to protect them from rain and direct sunlight. In order to be used as polymer fillers, stems had to be mechanically transformed to elongated fragments with a mean particle size in the order of 500 μm by first removing leaves and leaf sheath residues. Dried stem sorghum were then cut into smaller pieces of about 20 mm length by using a garden pruner. These 20-mm stem pieces were then ground in a Hellweg M50/80 granulator (Germany) designed for plastic pelletization and equipped with a 2.5 mm sieve. To ease the next milling step, the cut pieces were mildly dried in a Binder circulation air oven (FED line, Germany) at 60 °C for at least 5 h. Size was further reduced by a coffee mill (Carrefour home, France) for 40 s, with intervals of 10 s separated by 5 s

Table 1
Characteristics of the ten genotypes.

Genotype-partner-code	Code in this article	Seed origin	Race	Country of origin	Genotype type	Phenotypic characteristics (based on previous phenotyping trials)
IS19453	1	ICRISAT	Durra	Bostwana	Pure line	High NDF digestibility, low lignin content, high tolerance to pre- and post-flowering drought stress
IS20351	2	ICRISAT	Durra	Nigeria	Pure line	High juice content, high lignin content, low NDF digestibility
IS26731	3	ICRISAT	Bicolor	South Africa	Pure line	High sugar juice content, relatively low NDF content
IS30405	4	ICRISAT	Caudatum-bicolor	China	Pure line	Low juice content, high NDF content with low NDF digestibility
IS30417	5	ICRISAT	Caudatum-bicolor	China	Pure line	High lignin content
BN612	6	Commercial line	Caudatum	NA	Pure line	Double bmr mutant Bmr6 + Bmr12: low lignin content and high NDF digestibility
BIOMASS140	7	Eurosorgho	mixed	NA	Commercial hybrid: industrial use	High biomass production, high cellulose and sugar content
EUG341F: ES-Athena	8	Eurosorgho	mixed	NA	Commercial hybrid: silage use	High biomass production with high *in vitro* matter digestibility
RE1	9	Eurosorgho	NA	NA	Male parent of BIOMASS140	High NDF, low organic matter solubility, low NDF digestibility
AE1	10	Eurosorgho	NA	NA	Female parent of BIOMASS140	Short stem, high grain production, high digestibility biomass and NDF digestibility

NA: Not available, NDF: neutral detergent fiber.