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A 3-D finite element analysis of the sunflower (*Helianthus annuus* L.) fruit. Biomechanical approach for the improvement of its hullability

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Abstract

For the sunflower fruits, hullability (**H**) is a technical parameter that defines how easily the hull can be broken and set apart from the kernel. **H** mainly depends on the morphology of the fruit and the biochemical properties of the hull. Finite element analysis (FEA) was used to model the mechanical behavior of the sunflower fruit hull after the fruit impact. A 3-D model of an entire fruit was designed in terms of strain incompatibilities between two different tissues, parenchyma and sclerenchyma. Impact was simulated for three orientations of the fruit: longitudinal, transversal and lateral; and for two thicknesses of the hull: 100 μm and 300 μm. The validation of the FEA model was made based on a comparison of theoretical calculations and experimental data. It was noticed that the points of contact between the above mentioned tissues – with different mechanical properties – and the longitudinal parenchymatous rays of the hull were the main structural sites prone to fail mechanically after impact.

The simulated patterns of failure closely agree with those observed after subjecting fruits to compressive loading. The procedure described in this work could be useful to quantify and qualify, under different hull structural parameters, the distribution and magnitude of stresses generated in the hull during industrial mechanical hulling. It can be considered the first step of a protocol of analysis leading to a genetic improvement of **H**.

Keywords: Finite element analysis; Hullability; Hull; Impact analysis; Mechanical and fracture properties; Modeling; Pericarp; Sunflower

1. Introduction

Sunflower grains are botanically defined as fruits. They are composed by a thin outer shell, the pericarp, also known as "hull", that surrounds and contains the seed, usually named "kernel". The seed contains the largest proportion of oil that is found in a fruit (Seiler, 1997).

Sunflower fruits are hulled before they enter in the industrial process of oil extraction. Hulling consists in the separation of the pericarp from the seed. The hulling machinery used in the oil industry frequently is based on the principle of impact. Large propellers centrifugally throw the fruits at high speed (15–30 m s^{-1}) against a hard surface where their pericarps totally or partially break apart.

The pericarp accounts for 20–26% (dry basis) of the total fruit weight and is a brittle structure composed by different tissues which have different physical and biochemical properties. The two main ones found in a mature fruit are parenchyma and sclerenchyma (Esau, 1977). The later one has a high proportion of lignin (20–25% db; Seiler, 1997). These tissues are transversally and longitudinally arranged forming compact bundles defined as rays (Lindström, Pellegrini, & Hernández, 2000; Seiler, 1997).

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The ability of the pericarp to break and to separate from the seed can be quantitatively defined with an index named hullability (**H**) (Denis, Coelho, & Vear, 1994; Denis, Dominguez, & Vear, 1994). It is calculated as (MHW/THW) × 100, where: MHW = weight of the pericarp obtained using small laboratory hulling machines that simulate the industrial process and THW = total weight of the pericarp obtained by manual hulling.

The orientation of the fruit inside the hulling machine during the impact can affect the magnitude of the pericarp breakage during the process. **H** is higher if the fruit impacts longitudinally or transversally than if it impacts radially, on its convex sides (Leprince-Bernard, 1990). Moreover hullability is closely related to morphological, histological and biomechanical properties of the pericarp. Its magnitude mainly relies on various pericarp structural properties such as its thickness (Dedio, 1993; Dedio & Dorrell, 1998; Denis & Vear, 1996) and number of parenchymatic rays, cell lignification and moisture content (Beauguillaume & Cadeac, 1992; Gupta & Das, 2000; Leprince-Bernard, 1990).

Fruit and seed size (Morrison, Akin, & Robertson, 1981; Beauguillaume & Cadeac, 1992; Leprince-Bernard, 1990; Lindström et al., 2000; Tranchino, Melle, & Sodini, 1984) and oil content (Baldini & Vannozzi, 1996; Denis et al., 1994; Denis & Vear, 1996; Fick & Miller, 1997) play also a very important role in the magnitude of **H**.

Some of these properties could be genetically modified (Fick & Miller, 1997) or changed with environmental growth conditions (Dorrell & Vick, 1997) and crop management (Baldini & Vannozzi, 1996; Dedio & Dorrell, 1998).

Using biotechnological techniques it is now also possible to genetically transform the mechanical properties of plant tissues, particularly modifying the metabolism for lignin synthesis (Boudet, Kajita, Grima-Pettenati, & Goffner, 2003; Hepworth & Vincent, 1998; Pilate, Guiney, & Halpin, 2002; Ralph, MacKay, & Hatfiled, 1997; Whetten, Mackay, & Sederoff, 1998).

For improving **H** by using these novel technologies the optimisation of the histological architecture of the pericarp should be considered. The accurate definition of its constitutive tissues, how they are distributed in fruits with different **H** and its biomechanical properties are then important variables to be defined. In this particular case a more precise approach should be taken in order to specify, for each biostructural component, the best distribution and quality of tissues.

Predicting the localization of the yielding sites and quantifying the magnitude of stresses produced when the fruit impacts during mechanical hulling, may help to define the best tissue distribution and composition that conforms an optimised pericarp histological architecture.

If the stresses and deformation of the hull can be predicted, the interpretation of the results requires a knowledge of the relationships among stresses, strains, and failure i.e. cracking or splitting of the fruit caused by cell wall rupturing or tissue separation. This information then could allow us to efficiently use the available biotechnological tools to improve **H**.

Several theories of failure for plant tissue have been proposed (Niklas, 1992). Generally is assumed that plant tissue may fail when normal strain reaches a critical value. In this work the biomechanical identification of yielding sites in the pericarp were estimated using a numerical approach, validating the results with laboratory mechanical tests.

2. Materials and methods

2.1. Anatomy of the pericarp

The anatomy of the pericarp was studied in two sunflower genotypes with highly contrasting morphology, i.e. small fruits with thin pericarp (genotype Morgan MG2) and larger fruits with thick pericarp (genotype Morgan M734) from transverse, longitudinal and tangential sections of whole fruits. Sections were appropriately stained (Ruzin, 1999) to obtain a detailed location of the main tissues within the pericarp and to determine their distribution according to their lignification level. This information was used to elaborate a model of tissue distribution.

2.2. Biomechanical properties of the tissues

The modulus of elasticity of the main tissues (parenchyma [R_p] and sclerenchyma [T_e] rays; Niklas, 1992; Wainwright, Biggs, Currey, & Gosline, 1982), were calculated from tensile and compressive tests made on longitudinal pericarp's segments of known dimensions. We use a micromechanical testing device for small plant samples designed in our laboratory. It was based in a high precision electronic balance (AND ER-180A, A&D Co. Ltd., Japan), mounted on a cantilever system holding an automated small displacement screw driven by an actuator. Samples of 10.0–12.0 mm length and 2.0 mm width and thicknesses of 100 μm for genotype MG2 and 300 μm for genotype M734 were prepared from longitudinal pericarp segments of 25 fruits for each genotype. Samples were gripped in simple-side acting grips and pressed or pulled in three directions (longitudinally [L], radially [R] or transversally [T]) at 5 mm min^{-1}. Relative humidity of all samples was kept at 11% (db). Real time data were collected and downloaded to a PC. From the force–deformation relationships obtained, the transformed stress/strain relationships were used to calculate the elastic moduli of the main tissues (parenchyma and sclerenchyma) for each fruit's orientation (E_L, E_R and E_T).

Poisson ratios for each tissue component and orientation was estimated from data described in the literature (Niklas, 1992; Preston, 1974; Wainwright et al., 1982). Tissue density was determined from the weight of pericarp segments of known dimensions.

Structural elastic modulus (E_{st}; Rowe & Speck, 2000) and the rupture modulus (RM; Niklas, 1992) for the whole fruits of the two genotypes in three orientations was