# Compression of plant seeds assuming soft spheres

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## ABSTRACT

Seeds of vegetables and fruits, such as bilberry seeds, can cause problems when processing purees in larger scale. The mechanical properties of the seeds are therefore of interest, but have been studied poorly. One difficulty is the small size of some of the seeds, but also their irregular shape. In this study we compressed bilberry seeds with a size of about one millimetre. To be able to compare the resulting force from the machine to other materials we applied a model assuming incompressible spheres, i.e. their volume do not change. The results showed that we were able to eliminate differences in force caused by the geometry when the compressive stress was calculated using the proposed model. Dried bilberry seeds had larger compressive stress with increasing deformation compared to the wet seeds.

## INTRODUCTION

Nordic berries, such as bilberry (*vaccinium myrillus*, also European blueberry) and raspberry (*Rubus idaeus L.*) are high valued as a group of healthy foods mainly due to their high amounts of phenolic compounds specifically anthocyanins[1,2]. Their consumption is associated with positive health effects, such as reduction of cancer cells[2]. It is therefore of interest to process this type of foods in a larger scale. Their handling in a processing plant can, however, be challenging due to their numerous seeds that can clog equipment and lead to defective packaging. Those defective packages are a risk for microbiologic contamination. Therefore, an evaluation of their mechanical properties is of interest.

The seeds of a plant is the part developing after fertilization. It is in a resting state before germination is initiated and the seed contains food reserves, such as fats and proteins[3]. Due to their small sizes, typically ∼1 mm for bilberry seeds, it is challenging to measure mechanical properties. In general, a sample is cut in defined shapes, such as cuboids that can be drawn apart or cylinders that are pressed with defined contact area of the probe with the sample. Samples with irregular shapes can certainly also be measured, but as they have an undefined shape only the direct force can be measured, whereas the stress cannot be calculated. Thus, results of only the force cannot be compared to other materials as the sample size differs.

In this study we compressed bilberry seeds and used a modified model assuming incompressible spheres where the volume does not change, which is based on a model developed by Lin and co-workers[4].

## EXPERIMENTAL

Bilberry seeds were rinsed in tap water and placed on an Instron 5542 (Instron Ltd, Norwood, MA, USA). A probe of 2.37 mm diameter was used, which always was larger than the sample. The probe distance was tared in contact with the bottom plate and with the sample lowered until the force was rising, where the distance to the bottom was noted as the height of the sample. The distance was tared again when the probe touched the sample. Two different bulkhead speeds were used: 0.5 mm/min and 5 mm/min. The end of the test was set to 90% compression of the sample height. Both wet and dried seeds were evaluated. Drying of the seeds was conducted in an oven at 40°C over night. Reference points were set at 25% and 80% strain and a manual set point was used to mark the first peak corresponding to the first crack in the sample and the strain and force were extracted. The stress was calculated using the raw data of the instrument using MATLAB (R2020b, MathWorks, USA) according to Lin et al. (2008), as described below[4]. The Young's modulus was calculated from the first linear increase in compressive stress as a measurement of stiffness. Significant differences were calculated with XLSTAT Basic (2019.3.2, Addinsoft, New York, USA) using ANOVA and a confidence interval of 95%.

COMPRESSION MODEL

Bilberry seeds often have a slightly elliptical shape where the length varies slightly between 1 and 2 mm and a height of 0.5 to 1 mm. When they are uni-axially compressed between two flat surfaces the contact area will increase with the deformation. The following was assumed:

- the seed is spherical before compression
- the volume is constant
- the shape of the compressed seed remains axisymmetric.

Figure 1 illustrates a schematic of the sphere before and after/during compression with the penetration depth $\delta$, the points $M$ and $M'$ are the particle centres before and after compression respectively, $a$ is the radius of the contact surface, and $R'$ is the centre length to the lateral surface. The lateral profile is constructed to

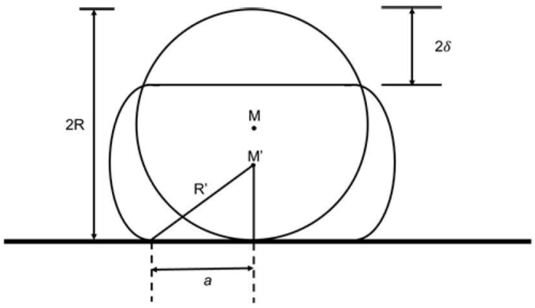



Figure 1: Schematic of a soft sphere being compressed and its physical quantities for the model. Adopted from Lin et al.

be spherical. The contact area with the surface $S$ can be calculated using the following equations:

$$a = \sqrt{R'^2 - (R-\delta)^2}, \quad (1)$$

$$S = \pi[R'^2 - (R-\delta)^2]. \quad (2)$$

The authors of Lin et al. divided the particle volume into two parts, which are the cylinder at the centre (where the contact surface is the bottom of the cylinder) and the two "shells" beside it[4]. The volume is then equal to the non-deformed particle, $3/4\pi R^3$ and the following equation can be obtained:

$$\frac{3}{4}\pi R^3 = 2\pi R'^2(R-\delta) - \frac{2}{3}\pi(R-\delta)^3. \quad (3)$$

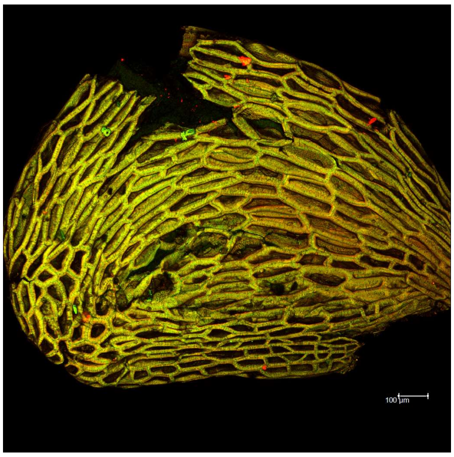
If eq. 3 and 2 are solved for $R'$ we receive the centre length to the lateral surface:

$$R' = \sqrt{\frac{2}{3}\frac{R^3}{R-\delta} + (R-\delta)^2}. \quad (4)$$

With that we can determine the changing contact area over time during the uni-axial compression using eq. 2 and finally calculate the compressive stress:

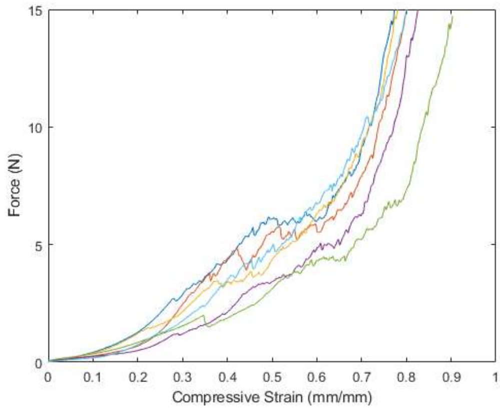
$$\sigma = F/S, \quad (5)$$


(a)

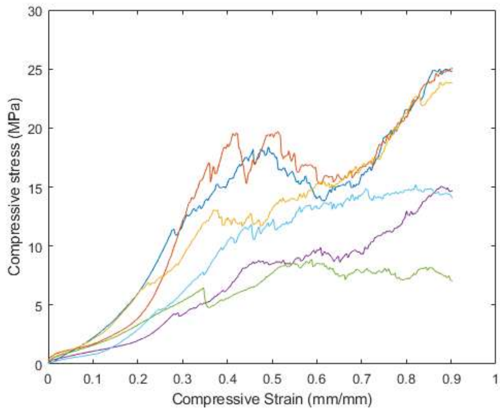



(b)

Figure 2: Light micrograph of a freeze-sectioned bilberry seed (a) and CLSM image of a compressed seed exhibiting auto-fluorescence (c). Scale bar is 100 µm in both images.




(a)




(b)

Figure 3: Compression profiles of **wet** bilberry seeds at a slow deformation rate, 0.5 mm/ min. of (a) force vs. compressive strain, and (b) compressive stress vs. compressive strain.

where $F$ is the force needed to compress the seed.

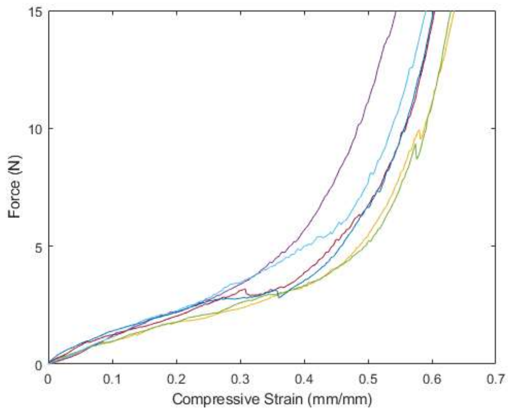
## RESULTS AND DISCUSSION

Bilberry seeds vary in shape, but have a somewhat elliptical shape in general and a mesh-like structure on the surface, as Fig. 2 illustrates. Fig. 2a shows a cross-section of a seed under the light microscope and Fig. 2b is an image of the shell of a compressed and broken seed that exhibits autofluorescence with a confocal laser scanning microscope.

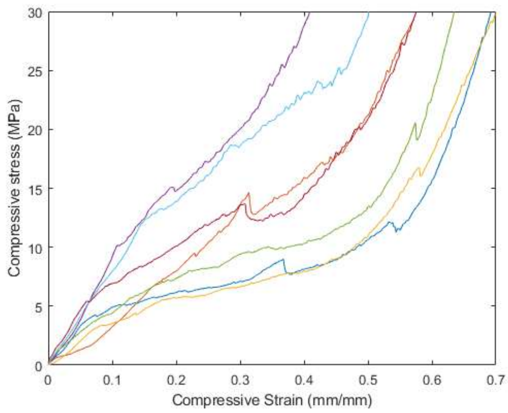
In Figure 3 some of the stress-strain curves (each line represents one individual seed) of wet bilberry seeds are plotted when they were pressed slow. The first graph (a) shows the force directly measured by the instrument and (b) illustrates the calculated stress according to eq. 5. As can be seen the individual seeds exhibit similar results and results are fairly reproducible, which shows that it is possible to measure the compression of such small objects with the instrument. The force increased exponentially (Fig. 3a). The calculated stress using the model increases more gradually, which is due to the change in contact area when the seed is compressed. The more it is compressed, the larger is the contact area which means that the stress increases less as compared to the force.

The fast stress-strain curves of wet seeds exhibited slightly smoother curves with fewer peaks, which can be the results of fewer measuring points (results not shown). Dried seeds exhibited stress-strain curves that drastically increased in compressive stress, even after the compensating for the increasing contact area as Figure 4a and 4b illustrates. The stress-strain curves of the dried seeds were generally smoother than for the wet bilberry seeds.

In Figure 5 the average of the measured force (a) and the calculated compressive stress (b) at the points of 25% and 80% are plotted, and the value at the first manually marked peak. The increased stress at larger deformations for the dried seeds is visible here at 80%, which exhibits a large difference to the other measured values. The difference is specifically high compared to the wet pressed seeds at the same deformation. When we compared slow and fast compression rates neither wet nor dried were significantly different at 25% deformation. Interestingly, when the same was calculated for the compressive stress, there was no significant difference between those samples. This indicates that the applied model has accounted for different sizes of the seeds and compensated the natural differences in seed size. As there were no differences in compressive stress between fast and slow compression rates, all stress values of the wet seeds were compared to all stress values of the dried seeds. There was a significant difference at 80% deformation (marked on the x-axis), which suggests that the seeds break differently when they are dry as compared to wet. This was confirmed by microscopy, which indicated that when the wet seeds were compressed the white interior was pressed out, while

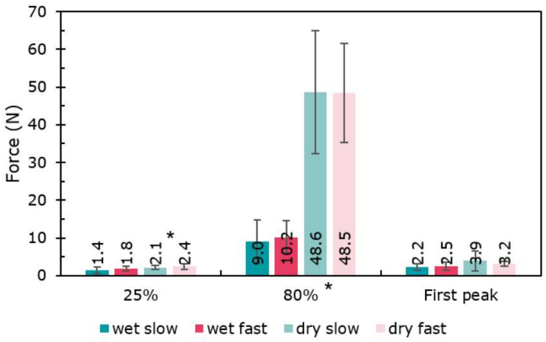



(a)

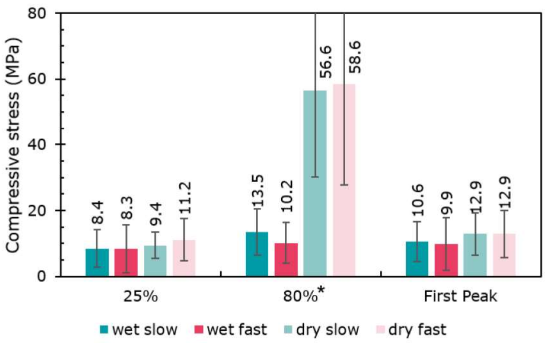



(b)

Figure 4: Compression profiles of **dry** bilberry seeds at a slow deformation rate, 0.5 mm/ min. of (a) force vs. compressive strain, and (b) compressive stress vs. compressive strain. The error bars represent the standard deviations.




(a)




(b)

Figure 5: Means of force (a) and compressive stress (b) at different deformations (25% and 80%) and the first marked peak. Error bars represent standard deviations and the stars mark significant differences.

for the dried seeds it remained inside and only a crack in the shell was visible.

The Young's modulus ranged from 44 MPa for the wet and fast samples to 71 MPa for the dried and fast compressed seeds. There was no significant difference between the samples. If the first peak in the profile is considered as the break of the seed it happened roughly at 31% compression irrespective of if the seeds were dry or wet or of the compression speed.

We speculate that the accuracy of the method decreases with higher deformation with respect to the sample that is not fully incompressible, and also when the shape deviates from spherical. However, in this study the aim was to get an estimation of the stress that is needed to compress the seeds rather than exact values to be able to compare to other materials and tissues. Gibson et al. compared the mechanical properties of different plant material tissues and their plant structure[5]. For example the compressive stress of wet potato tissue is about 1.3 MPa, and the Young's modulus 3.6 MPa. Other vegetable tissues have similar Young's modulus like apple (0.3–5.8 MPa) or carrot (2–14 MPa)[5]. In comparison cellulose, the main structureal fibre in the plant kingdom has a Young's modulus of 167 GPa in its crystalline form along the chain axis estimated from lattice dynamics modelling[6], and lignin and hemicellulose has 2.5–3.7 GPa, and 5–8 GPa respecitvely, which was obtained by pressing powder into a compact in a mould and conducting compressive tests[5]. Bilberry seeds are in comparison stiffer than potato parenchyma, but weaker than cellulose, lignin or hemicellulose.

## CONCLUSIONS

We have compressed seeds in the size of roughly one millimetre, specifically bilberry seeds with an Instron testing machine. To be able to compare strength and modulus to other materials we used a method to calculate the compressive stress assuming the seed to be spherical and incompressible. The results showed that we were able to compensate for differences in the geometry using the proposed model. The dried bilberry seeds resulted in a larger compressive stress with increasing deformation compared to the wet seeds. In comparison bilberry seeds can be considered stiffer than vegetable tissue, but softer than crystalline cellulose, lignin or hemicellulose.

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