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Experimental method to analyse the blackspot bruises of potato tuber flesh due to mechanical deformation

Lukas Poppa, Ludger Frerichs, Jintian Liu, Markus Böl

Continuous improvements in potato harvesting and storage techniques in recent years have reduced external potato damage such as shatter or skinning. However, the internal tuber damage caused by mechanical stress, i.e. blackspot, cannot be sufficiently reduced with conventional development tools such as field trials. Due to the approximately two-day duration of the blackspot development following the mechanical stress, it is often unclear in which process step and under what environmental conditions the damage occurs.

Particle simulation of agricultural harvesting processes offer extensive opportunities to improve machine processes and reduce harvesting losses. Using the Discrete Element Method (DEM), it is possible to gain a deep understanding of the harvesting and transportation processes of potatoes. The DEM represents potato tubers as particles and machine components as geometry elements. The geometry elements can be stationary or follow predefined movements, while the particle motion is calculated based on contact laws and material properties. The global particle model of DEM can predict contact stresses on a particle level, but is unable to describe local damages such as blackspot. This paper introduces a test rig for investigating mechanically induced discoloration of potato tissue and describes a model for representing local blackspot damage in DEM.

Due to the inhomogeneous composition of the potato tuber with multiple tissue types, the three primary tissue types: cortex, perimedullary parenchyma and pith tissue are examined separately on the developed test rig. The mechanical stress on the tissue samples is applied up to a maximum compression strain of 20, 40, and 50%, with a defined strain rate ranging from 0.1 to 10000% per second, relative to the sample height. The colour change of the samples is examined after approximately 48 hours against unloaded reference tissue. The tests were conducted at a tuber and ambient temperature of 14–20°C. The correlation between the colour change and the load parameters, compression strain and strain rate, can be described by an empirical equation. By implementing this equation as a damage model in the DEM contact model, the origination of blackspot in real processing stages can be predicted and investigated in simulations. The damage value of individual particles can be compared with the damage observed in real potatoes, allowing for the validation of the damage model.

Keywords
Blackspot, potato, simulation, damage model, experiment

Potato is worldwide an important nutrition source and one of the main staple foods besides cereals. Over 350 million tons are harvested each year around the world with different levels of mechanisation (FAO 2021). If potato tubers are damaged during harvest, their storability is reduced due to the risk

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of mould and their marketability is reduced due to cosmetic defects, which results in a financial loss for the farmer (Peters 1999). Tuber damage mainly occur during handling and transport and can be classified into external damages and internal damage (Hughes 1980, Heinecke 2007). The susceptibility of blackspot also strongly depends on tuber physiology (Wulkow 2009). External damage to the potato skin and the underlying tissue occurs with strong impacts or through friction. Small and medium impacts can damage vacuoles for starch storage within the cells. Enzymatic and chemical reactions lead to the formation of melanin and the discolouration of the cell, which eventually becomes visible as blackspot (Heinecke 2007). Stronger impacts can destroy the cells inside of the tuber and produce cavities that facilitate bacterial infections. Blackspot can thus develop from a cosmetic defect to a potato rot problem. A higher number of spoilt potatoes can lead to a spread of the infection to undamaged potatoes as well due to the increased load of pathogens and the associated rise in temperature, thus spoiling the entire stock. External tuber damage and shattering are easy to identify, as they are directly visible during harvest and can be reduced or eliminated by changing machine settings or the harvesting processes. Reducing blackspot bruises poses the main challenge as they become visible only after a storage time of ca. 48–72 h and can only be examined after peeling the tubers. Nowadays, the right adjustment of machine settings to reduce tuber damage under changing harvesting conditions depend on the experience of the machine operator. The time delay between harvest and blackspot development as well as various interfering environmental conditions renders automatically correcting machine settings impossible. Therefore, field test are unsuitable to further optimise machine and machine settings.

The Discrete Element Method (DEM) is a suitable tool to simulate granular materials in handling processes and is commonly used in agricultural engineering (Tijskens et al. 2003). The numerical mesh free method is able to simulate three-dimensional movement of granular material depicted as particles and was originally developed by Cundall and Strack (1979). The particle movement during simulation is calculated according to the Newton`s laws of motion and changes direction while interaction with other particles or machine parts depicted as geometry elements. Additional field forces like gravitation or electromagnetic fields can be considered for the particle movement. Particles can be represented by polyhedral bodies to account for specific shapes of the granular material, but the application of sphere-based elements, e.g., clump with overlapped spheres, has shown great advantages in many simulation studies due to the relatively low computational costs (Coetzee 2020). Particles and geometry elements are considered rigid and the interaction force between two particles or a particle and a geometry element is governed by the calculated overlap and the contact model. The DEM-based simulation shows advantages in fast assessment of new machine settings and optimisation of harvesting processes under controlled ambient conditions. Unfortunately, the lack of information on local stress estimation inside the particles and the corresponding damage degree results in inaccurate prediction of process quality, namely also the disadvantage of field tests.

In this context, the DFG project “A comprehensive model for the prediction and analysis of internal potato tuber damage in postharvest processes” aims to propose a damage model for potato tubers in a simulation model. In this project, the internal damage due to various stress factors will first be analysed based on the discolouration of the potato tissue, followed by the development of a damage model on the tissue scale, the subsequent extension of the simulation model by integrating the damage model and finally the validation of the model.

This paper shows first steps to develop the tuber damage model: The test procedure to deform a tissue under controlled environment and measure the colour change of tissue due to deformation (Figure 1). The single steps of the test procedure are:

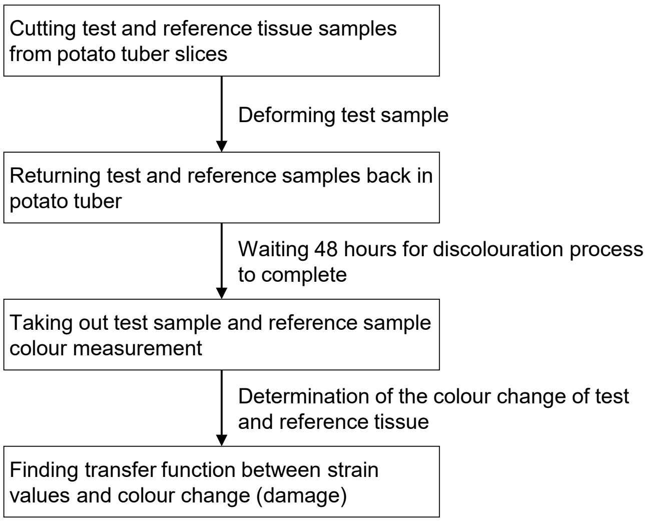

Figure 1: Test procedure steps for deformation and measurement of the resulting colour change of potato tissue

Materials and methodical procedure

Test potatoes and tissue types

Potato tubers of the Afra variety, with a particularly high blackspot susceptibility (Bundessortenamt 2015) were used for the investigations. To prevent preliminary damage, the potato tubers were harvested as gently as possible using a windrower and then selected and collected by hand. With this method, the loads on the tubers were minimised and no external or internal tuber damages were observed on the tuber tissues to be tested. In order to reduce the influence of the tuber physiology on the obtained results, the tests are conducted in narrow time windows. Additionally, only tubers of the square size 50 to 55 mm are used for the experiments. The potato tubers were stored at ideal conditions of 5 °C and about 99 % rel. humidity. The tests were conducted a few days after harvest and repeated after 4 and 8 months of storage. Potato tubers harvested in 2021 and 2022 from one field each were tested.

The inhomogeneous structure of potato tubers requires the analysis of the three inner tissue types. The cortex tissue is an approx. 4 to 10 mm thin layer under the potato skin. The perimedullary parenchyma tissue, also called perimedullary zone (PZ), ranges from cortex tissue to the tuber center and constitutes the major part of the potato tuber. PZ usually experiences intense discolouration caused by blackspot. The pith tissue locates in the centre of the potato and is more translucent due to a higher water content.

Considering the limited thickness of cortex tissue, small cylindrical samples with dimensions of 3.5 mm in diameter and height were prepared for the mechanical experiments. From each of two slices per tuber a test and its corresponding reference tissue sample were cut according to the given dimensions using a custom-made die cutter and cutting device. The reference sample is necessary to eliminate the colour variance within different tubers by determining the relative colour change between tested and reference samples from same tuber. Preliminary tests have shown that the Hue value in the HSV-colour space can be considered as the most obvious indicator of discolouration and a colour change of $\Delta Hue = -5°$ Hue can be identified once blackspot is established.

For this purpose, cylindrical test and reference samples are taken from potato slices. The test samples are then loaded with predefined compression strain and strain rate. After loading, the test samples and the unloaded reference samples are stored in the potato slices in darkness for approx. 48 hours at room temperature to complete the discolouration. The test and reference samples are then removed from the slices again and the colour change is examined by photographic imaging.

Experimental setup for precise deformation of tuber tissue

Bruising damage of tuber is usually induced by impacts against machine parts or other tubers. Drop heights range from 200 mm in harvesting processing stages, to 500 mm while overloading into trailers or storage boxes. These result in relatively high strain rates of 1980 %/s to 3130 %/s in relation to a tuber length of 100 mm. After harvesting, further tuber handling processes, like grading or cleaning include varying drop heights from 20 mm to 200 mm as well as quasi-static loads during storage with therefore very low strain rates.

Considering these variances, a test rig for fast dynamic load on tuber tissue was developed as shown in Figure 2. The tissue samples are placed on a high sensitive piezoelectric force transducer (9323AA, Kistler Instrumente AG, Switzerland). An electric servomotor is used as actuator to rotate the lever at a specific rate. The lever hits and deforms the sample to a specific strain limited by an adjustable dead stop. Due to the long lever of 200 mm and the small deformation of maximal 1.75 mm, the inclination effect is negligible and the sample deformation can be considered uniaxial. In addition to the force signal, the deformation of tissue sample is characterised by tracking the movement of the lever using a high-speed camera (NX8 S2, Integrated Design Tools Inc., U.S.A.) with up to 20000 Hz. With the measured compression force and the estimated deformation based on recorded images, important material values for the simulation model can be gathered. For the slow quasi-static loading, however, the strain-controlled compression tests were performed using a universal testing machine (Z0.5, Zwick GmbH, Germany) equipped with a 20 N load cell. The tuber samples were hydrated in isotonic solution to prevent drying and swelling during the quasi-static loading periods. With this experimental setup, the compression tests were performed using three different maximum strains of 20, 40 and 50 % and six different strain rates in logarithmic steps from 0.1 to 10000 %/s relative to the initial sample height. The experiments were conducted on the three stated tissue types, each with eight replications, resulting in a total of 432 experiments for each investigated harvest year and storage duration.

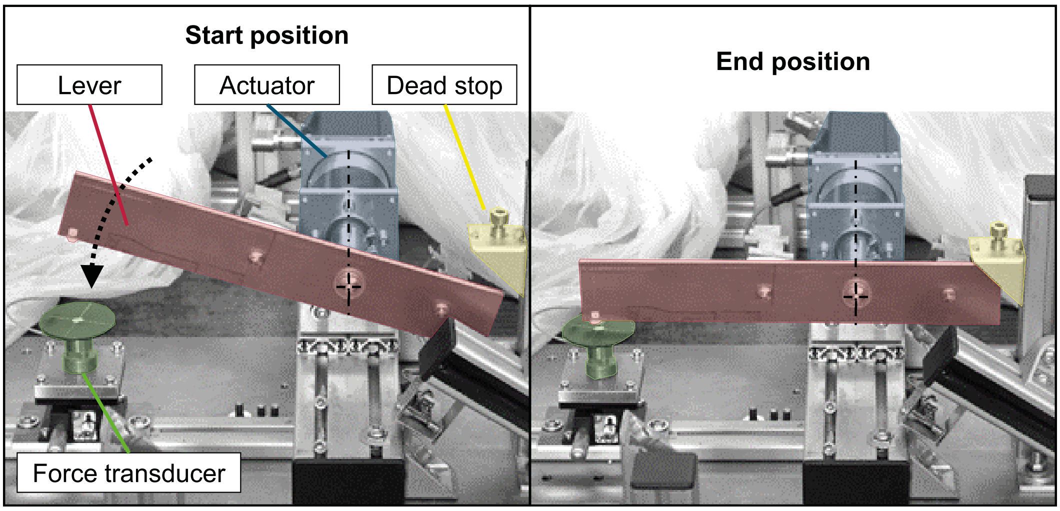

Figure 2: Test rig for dynamic deformation of potato tuber tissue samples

Measuring setup to analyse discolouration

After storing the test and reference samples for 48 hours to induce the biochemical discolouration, they are taken from the tuber slices and photographed in a rack. Figure 3 illustrates the test setup on the left side and an example picture on the right side. To eliminate the influence of surrounding light sources, the pictures are taken in a darkroom and LED Lamps with wide colour spectrum of CRI > 95 are used.

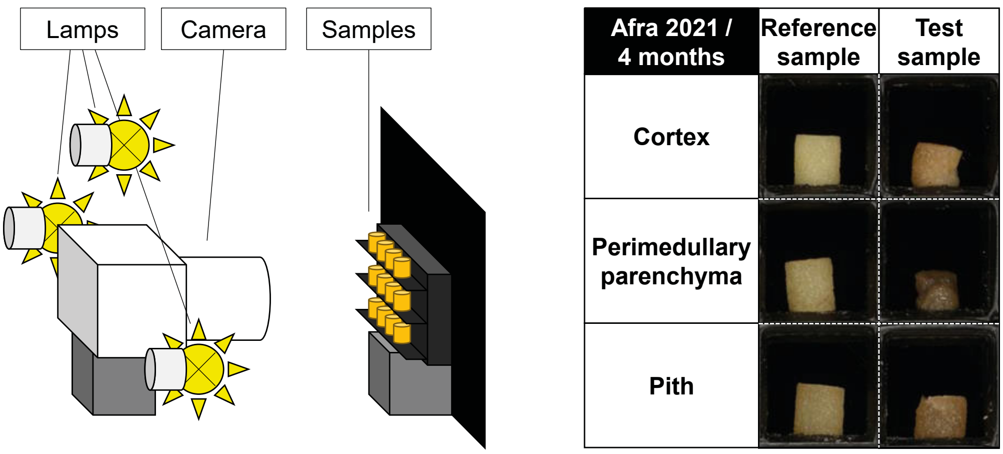

Figure 3: Measuring setup to analyse discolouration (left) and example tissues at δ = 40% and $\dot{\delta}$ = 10000%/s (right)

Images are processed with Matlab (The Mathworks Inc., U.S.A.) and categorised with respect to tissue type, applied maximum compressive strain and strain rate. After removal of the black background and segmentation of the regions of interests from the test and reference samples, the mean hue value of the cropped regions is determined in the HSV colour space. The relative colour change between tested and reference sample is allocated to the given experiment settings.

Experiment results and discolouration function

The discolouration of the PZ tissue is shown for different strains and strain rates in Figure 4. The discolouration features a strong dependency on both strain and strain rate. The load case with high strain and high strain rates show severe discolouration whereas slow strain rates or low strain do not result in obvious damage.

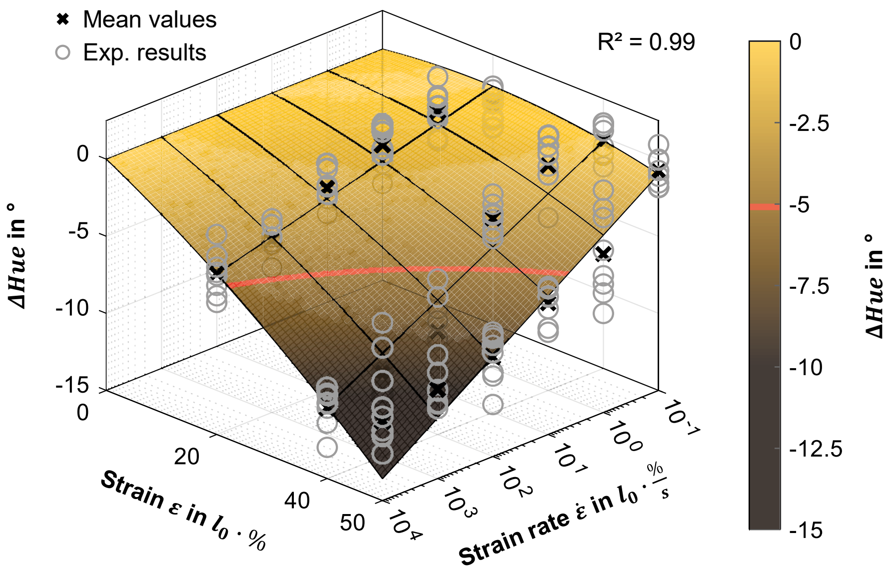

Figure 4: Discolouration of perimedullary parenchyma depending on strain ε and strain rate $\dot{\varepsilon}$ of fresh potato tuber

The dependence of the change of hue value ΔHue on strain ε and strain rate $\dot{\varepsilon}$ can be formulated by a transfer function using the "surface fit" algorithm of Matlab. A quadratic relationship to the change of hue value was assumed for the compressive strain, the logarithm of strain rate and their interdependence. By removing coefficients with small effect, the relation was reduced to the following discolouration function (equation 1):

$$\Delta Hue = k_1 \cdot \varepsilon^2 + k_2 \cdot \varepsilon \cdot \log(\dot{\varepsilon}) \qquad \text{(Eq.1)}$$

The discoloration function with coefficients of $k_1 = -1.4 \cdot 10^{-3}$ and $k_2 = -5.0 \cdot 10^{-1}$ results in a high coefficient of determination of $R^2 = 0.99$ and is visualised as surface plot in Figure 4. The threshold value for blackspot damage is visualised in the surface as red line at a change of hue value of −5° *Hue.* The influence of long storage times of tubers on their discolouration susceptibility is shown in top left and top right diagrams in Figure 5. The damage susceptibility of PZ tissue reduces significantly over storage time of eight months. Similar effects can be observed as well for cortex and pith tissue and is therefore not displayed. Even with low cell activity at ideal storage conditions, the tubers loose water due to cellular respiration. Presumably, the reduced turgor is the reason for less influence of strain rate on the discolouration. The effect of high strain increases slightly for the stored tubers. The standard deviation of discolouration for different settings increases due to different tuber development over the long storage duration. The two diagrams at the bottom show the damage susceptibility of pith and cortex tissue for harvest-fresh potato tubers. Both tissues are significantly less sensitive to the discolouration induced by mechanical load than PZ tissue with pith tissue being most resistant.

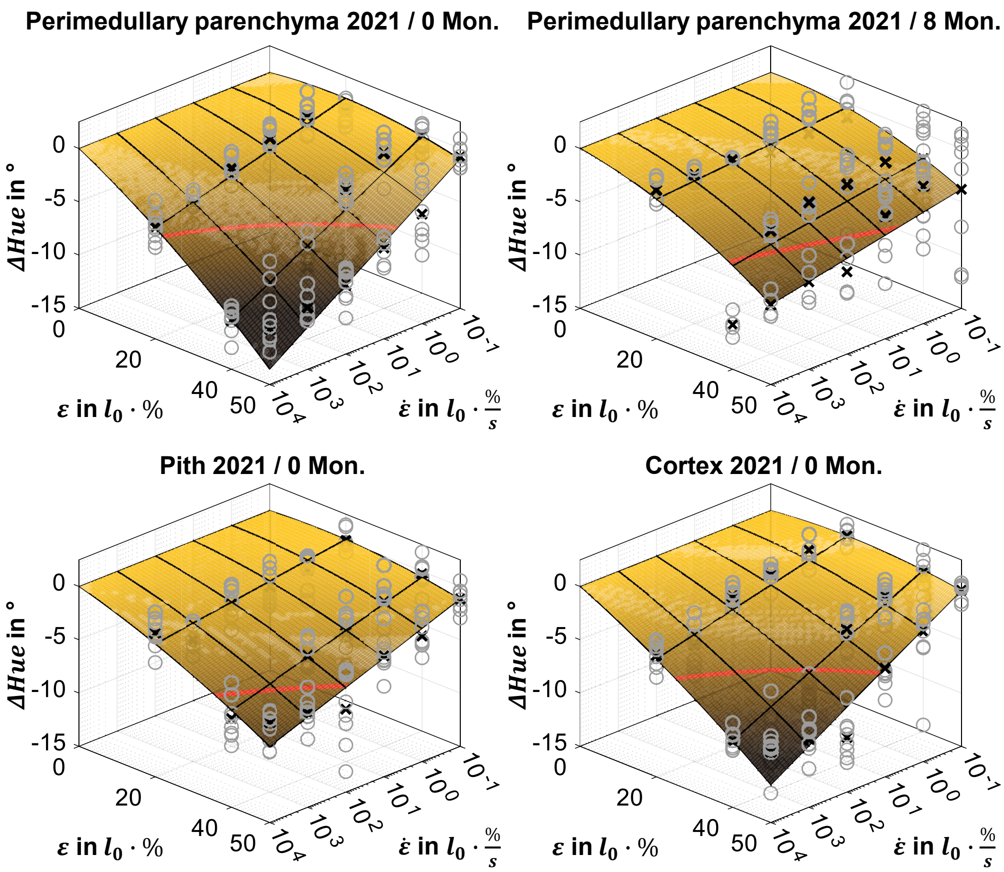

Figure 5: Discolouration susceptibility after different tuber storage times and tissue types for 2021 harvested tubers

In Figure 6, the discolouration sensitivity of fresh potato tubers from two consecutive crop years can be compared. A clear reduction in discolouration susceptibility can be observed for crop year 2022. Additionally, the mineral content of potato tubers from crop year 2022 was investigated and a high potassium content of 2.5% of dry matter was found. A solid potassium nutrition can reduce the blackspot vulnerability and thus the discolouration susceptibility of the potatoes (Heinecke 2007).

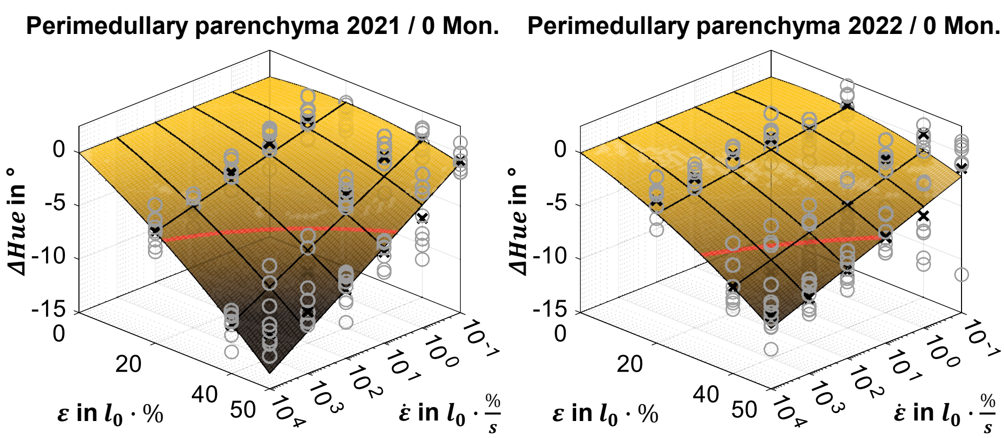

Figure 6: Discolouration susceptibility of perimedullary parenchyma of harvest-fresh tubers of different crop years

To transfer the discolouration susceptibility into a discrete element method model, the discolouration susceptibility of the perimedullary parenchyma is primarily relevant. On the one hand, this is due to the higher blackspot sensitivity and, on the other hand, to the high proportion of this tissue in the potato tuber. The following table compares the constants k_1 and k_2 of the discoloration function previously described for the examined tissues of the perimedullary parenchyma of the different storage durations and crop years (Table 1). The coefficient k_2 defines the basic trend of the discolouration function. A reduction of the discolouration susceptibility over the storage conditions as well as an reduced discoloration susceptibility for the 2022 harvested potato tubers can be observed. The coefficient of determination shows high to very high correlation of the discolouration function and experiment data.

Table 1: Discolouration function values of the discolouration susceptibility of perimedullary parenchyma

Coefficients of the discoloration function	Crop year/storage duration			
	2021/0 month	2021/4 month	2021/8 month	2022/0 month
k_1	−1.4E−03	−5.1E−04	−1.8E−03	−1.5E−03
k_2	−5.0E−02	−4.3E−02	−1.3E−02	−3.8E−02
R^2	99%	86%	97%	92%

To simulate blackspot in the Discrete Element Method, the discolouration function can be integrated in the following as damage function in an expanded contact model. By segmenting the particles with discrete increments, local damages can be detected despite the global particle model (Figure 7, middle). Segments with a calculated $\Delta Hue \leq -5°$ are defined as damaged according to the experiment results. An example of blackspot distribution obtained from experiment (left) and estimated by simulation model (right) is shown in Figure 7. In subsequent steps, the damage model must be validated through the comparison of damages in experiments and simulations.

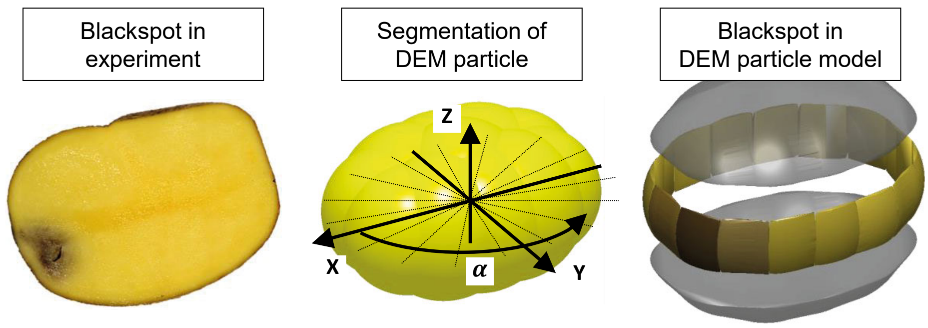

Figure 7: Blackspot due to mechanical load in experiment (left), segmentation of the DEM particle (middle) and simulation model (right)

Conclusions

The developed experiment setup is able to precisely load the tissue samples. The induced discolouration can be determined with the test procedure and the measuring setup. The induced discolouration can be determined with the test procedure and the measuring setup. The combination of high compressive strain and high strain rate induce severe blackspot discolouration. Perimedullary parenchyma is most and pith is least susceptible to blackspot damage according to relative discolouration values. Long storage durations reduce discolouration susceptibility presumably due to reduced turgor. Discolouration of the different tuber tissues is significantly influenced by strain and strain rate and can be described with transfer functions. Through the segmentation of potato particles within the DEM simulation environment and the experimentally determined discolouration function, local blackspot damage can be visualized in the simulation. In future investigations, the relationship between the discoloration function and tuber physiology will be more thoroughly examined.

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Authors

Dipl.-Ing. Lukas Poppa is a research assistant and **Prof. Dr. Ludger Frerichs** is the director of the Institute of Mobile Machines and Commercial Vehicles at Technische Universität Braunschweig, Langer Kamp 19a, 38106 Brunswick, Germany, e-mail: l.poppa@tu-braunschweig.de

Dr.-Ing. Jintian Liu is a research assistant and **Prof. Dr.-Ing. Markus Böl** is the director of the Institute for Mechanics and Adaptronics at Technische Universität Braunschweig, Langer Kamp 6, 38106 Brunswick, Germany.

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