# ABSTRACT

Cryogenic grinding (cryo-grinding) method is widely practiced to obtain high quality of spice powder. However, the cost involvement with the method is still high mainly due to lack of insight into the process. Discrete element method (DEM) is one of the advanced numerical techniques used to study micro-mechanical behavior and heat transfer phenomena of granular food in the particulate system. In the present investigation, DEM simulations were utilized to study the flow, breakage, and heat transfer characteristics of black pepper (*Piper nigrum* L.) seeds in a laboratory scale cryo-grinding system: precooler and hammer mill at an optimal grinding temperature. Further, response surface methodology was used to optimize the grinding temperature (−120 to 40 °C) with the aim of obtaining maximum flowability and sensory quality of powder. Appropriate contact model(s) with a set of input parameters were selected in DEM simulations, to achieve the aim of this study. Calibration test was used to select the complete set of DEM input parameters using standard method(s). Moreover, some of the parameters (thermal and mechanical properties) were measured experimentally in sub-zero temperature regime (−45 to 5 °C) at 3.9% dry basis (d.b.) moisture content of the sample.

The optimum cryo-grinding temperature was −43 °C with the highest desirability value of 0.57 for 1.5 kg $h^{-1}$ feed rate, 26 m $s^{-1}$ peripheral speed of the mill, and 3.9% d.b. moisture level of the sample. The optimally cryo-ground powder had 98.8 μm particle size, 38.9° angle of repose, 1.17 Hausner ratio, 1.24 ml $(100\ g)^{-1}$ volatile oil content with a total color difference < 0.24. The temperature showed a significant effect on the thermal and mechanical properties. In DEM simulation, 70–80% of the seeds were retained in the rotating direction of screw shaft along with the highest granular temperature observed close to the wall of the precooler. The granular temperature (maximum) in hammer mill followed this order: right side > left side > bottom side of the mill. Furthermore, findings of particle breakage also supported the proposed granular heat transfer model in the mill. The observed qualitative and quantitative results (maximum granular temperature, dynamic angle of repose, and flow pattern) of numerical and experimental approaches were in good agreement. In conclusion, the aspects of granular motion, breakage, and heat transfer in the cryo-grinding system were critically analyzed with a convincing insight of the micro-mechanical phenomena.



**Keywords:** Black pepper, cryogenic grinding, discrete element method, optimization, simulation, heat transfer