

# Sustainable granulation of limestone fertilizers using molasses-vinasse binder mixtures: a circular economy approach

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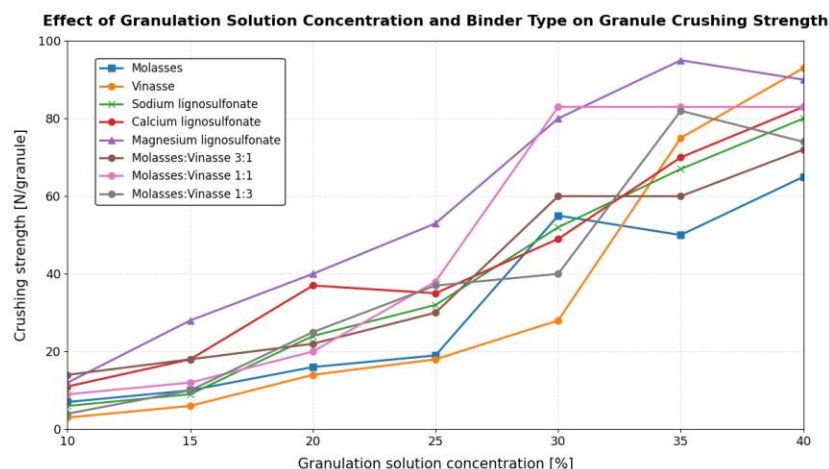
Soil acidification is a critical agricultural challenge affecting over 50% of Polish arable land, with some regions exceeding 70% acidity levels (Ochal, 2020). While the theoretical lime requirement for soil restoration is approximately 2 t CaO ha<sup>-1</sup> (Jadczyzyn & Lipoński, 2022), actual application rates average only 0.09 t CaO ha<sup>-1</sup> year<sup>-1</sup> (Barczyk-Ciuła et al., 2024), primarily due to handling difficulties with powdered limestone products. Granulated fertilizers offer significant advantages, including uniform field application, reduced dust emissions, and compatibility with blending with other granulated fertilizers. However, conventional granulated liming products face a critical quality-cost trade-off: those produced with water alone exhibit **poor crushing strength and high abrasion loss**, leading to significant transport and spreading issues, whereas high-quality alternatives are 4–6 times more expensive than powdered equivalents due to costly commercial binders such as lignosulfonates.

This study introduces a sustainable and innovative granulation approach utilizing industrial by-products from the food and fermentation industries – **molasses and vinasse** – as cost-effective, multifunctional organic binders. The key novelty lies in the systematic evaluation of **binary molasses–vinasse mixtures** at varied mass ratios (3:1, 1:1, 1:3 on dry matter basis) as granulation agents for milled limestone – a combination not previously described in the scientific literature. The research objective was to develop an economically viable and environmentally sustainable granulation process for activCALC (FHP MKG PROMYK), a high-quality limestone characterized by neutralizing value >55, reactivity >98%, and median particle size Dv50 = 10.2 μm. These industrial side-streams represent a versatile binding platform applicable to a wide range of granulated materials, thereby contributing directly to circular economy principles by valorizing streams that would otherwise constitute waste.

The binders evaluated were: molasses (80% w/w solution, sugar industry, ~480 PLN/t), vinasse (VINASSA VINALAL, Lallemand Sp. z o.o., Józefów, Poland; 47% w/w from yeast fermentation, ~650 PLN/t at 65% conc.), their binary mixtures at three mass ratios, and sodium lignosulfonate (Wal-Mar Sp. z o.o.; powder; 3300 PLN/t). Binder solutions at concentrations of 10–40% w/w were tested; water served as the reference. Laboratory-scale granulation (56 trials) employed a 400 mm disc granulator (16–17 rpm, tilt 30–60°) processing ~3 kg batches; binder solution was applied via manual sprayer (Kwazar, 1 L) until the target 2–6 mm granule size was achieved, followed by drying at 105°C for ~1 h. Pilot-scale trials (9 trials) were performed at the Łukasiewicz-INS Fertilizer Research Center on a semi-industrial plant comprising a paddle granulator (primary agglomeration, ~90% of feed), a 115 cm diameter disc granulator (secondary growth), a co-current rotary dryer (70 cm × 4 m; inlet air 120–130°C), a three-deck vibrating screen classifier, and a recycle loop (10–30% of output) with SCADA monitoring. Production capacity reached 160–180 kg h<sup>-1</sup>.

Quality was assessed by standardized methods: particle size distribution by mechanical sieving (PN-EN 1235:1999+A1:2004); crush strength with ERWEKA TBH 225 (20 granules per fraction, 2.0–5.0 mm range); wet sieving stability per PN-EN 15704; abrasion resistance in ERWEKA TAR drum (50 g, 30 rpm, 20 min); moisture content by gravimetric drying (105°C to constant mass); reactivity by potentiometric titration (PN-EN 13971); and raw limestone particle size by laser diffraction (Mastersizer 3000, Aero S dry dispersion).

Laboratory results demonstrated significant strength improvements across all organic binders versus the water-only reference (5–10 N/granule). Molasses at 30% concentration achieved 20–25 N/granule with ~3% d.m. addition (cost ~27 PLN/t product). Vinasse at 40% concentration reached 85–95 N/granule (cost ~47 PLN/t at 5% d.m.).



Critically, the **molasses:vinasse mixtures at 30% concentration exhibited synergistic binding effects** (with ~3% d.m of binder in total mass), yielding 45–85 N/granule with a pronounced 24-h post-granulation strength of granules increase attributed to continued cross-linking within the organic matrix. Due to the low binder content and high granule strength, this formulation achieved optimal cost-effectiveness at 20–25 PLN/t of product. All organic binder products after standard classification

exceeded 97% in the target 2.0–6.3 mm fraction ( $d_{eq} = 3.2\text{--}4.2$  mm). Wet sieving tests (PN-EN 15704) confirmed complete granule disintegration for all trial products, meeting agronomic soil-reactivity requirements. Abrasion loss improved from 15–20% (water reference) to <5% with organic binders.

Pilot-scale results confirmed the laboratory findings at larger scale. The water-only reference trial produced granules with only ~69% in the 2–6 mm fraction and abrasion loss of ~31%, confirming the inadequacy of water as a sole granulation agent. The 1:3 molasses:vinasse mixture at 30% delivered the lowest abrasion loss of 0.07% with 98.4% in the target fraction. Mean crush strength in pilot trials ranged from 5 to 20 N/granule, increasing substantially after 24-h seasoning. Product moisture content was consistently 1.0–2.0% w/w. Drying temperatures were kept below 100°C in the product zone to prevent rapid steam release and associated granule fracture.

The significance of these findings extends beyond the limestone products. Molasses and vinasse are abundant, low-cost industrial by-products with favorable rheological properties for granulation processes. Their use as a binary binder system in limestone fertilizer granulation has not been reported in the scientific or patent literature. Preliminary patent analysis indicates this constitutes a patentable invention, and a patent application was prepared for submission to the Polish Patent Office (UPRP). At the commercial level, the results provide a scalable route to higher-quality granulated liming agents at costs competitive with current water-only production, directly addressing the central market challenge of the quality-cost trade-off in this product category.

Organic binders from agro-industrial by-products – molasses, vinasse, and their binary mixtures – substantially improve the physico-chemical quality of granulated limestone fertilizers. The molasses:vinasse binary system at 30% concentration provides the best combination of crush strength (45–85 N/granule), low abrasion loss (<3%), high target-fraction yield (>98%), complete water disintegration, and low binder cost (~25 PLN/t product). The research delivers a comprehensive process dataset and upscaling guidelines supporting Stage III industrial trials at the MKG PROMYK facility, and contributes novel knowledge to the field of sustainable, circular-economy-based fertilizer granulation technology. The binary molasses–vinasse binder system represents a patentable innovation with potential applicability across the broader bulk material granulated sector.

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