# Electroactive Nanocellulose Biolubricant Under Electric Fields: Squeeze-Flow Evidence of Improved Load Carrying Capacity

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**Abstract**
The development of environmentally sustainable lubricants capable of actively adapting to changing operating conditions is of increasing interest in tribology. Conventional anti-wear additives and nanoparticle-enhanced lubricants, while effective, rely on passive mechanisms and often raise environmental concerns. Electrorheological (ER) fluids offer a promising alternative by enabling real-time modulation of rheological properties and tribological behaviour through the application of an external electric field. Building on this concept, the present work investigates the squeeze-flow behavior and load-carrying capacity of novel electroactive biolubricants formulated from castor oil and crystalline nanocellulose (CNC), nanoparticle selected for its sustainability, polarizability, and ability to form field-induced structures.

## 1. Introduction
An early study by Korenaga et al. [1] demonstrated a remarkable fourfold increase in lubricant film thickness when a low molecular weight liquid crystal was used in an electrified tribological contact. This enhancement was attributed to the so-called electro-viscous effect. In contrast, and in alignment with the Sustainable Development Goals (SDGs), we advocate for simple and environmentally friendly lubricant formulations based on nanocrystalline cellulose dispersed in castor oil, which have also demonstrated electrorheological (ER) behavior.

Previous studies demonstrated that these ER biolubricants undergo electro- and shear-induced structuring [2], suggesting that electric fields could be used to dynamically enhance their in-service performance. Here, we examine whether such structuring translates into improved resistance to compression under electrified parallel-plate conditions, a key indicator of load-carrying capacity in tribological contacts.

## 2. Materials and Methods
Castor oil, supplied by Guinama (Spain), was selected as the base fluid due to its favorable physicochemical properties. At 25 °C, it exhibited a dynamic viscosity of 735 mPa·s. Commercial crystalline nanocellulose (CNC) was obtained from Nanografi Co. Ltd. (Turkey). Produced via sulfuric acid hydrolysis, resulting in the presence of sulfate groups, CNC particles have diameters ranging from 10 to 20 nm, lengths between 0.3 and 0.9 µm, and exhibit 100 % crystallinity as determined by X-ray diffraction (XRD).

The CNC in castor oil biolubricants were prepared by ultrasonic homogenization using an UP400St device (Hielscher, Germany), with a total energy input of 7 Wh per sample. To prevent thermal degradation, the temperature was maintained below 75 °C by placing the containers in an ice bath throughout the process. Tests were performed across a range of nanoparticle concentrations between 0.5 and 6 wt.%.

Squeeze-flow experiments were conducted using a strain-controlled ARES-G2 rheometer (TA Instruments, USA) equipped with 25 mm smooth parallel plates, with initial gap of 500 µm, applying a constant approach velocity of 0.5 µm/s under a DC voltage of 300 V. The required voltage was delivered using a Keysight 33210A function generator (Agilent, USA) in combination with a Trek 609E-6 high-voltage amplifier (Trek Inc., USA). For the sake of comparison, tests were also conducted in the absence of voltage.

## 3. Results and discussion
Results reveal that CNC-based biolubricants exhibit compression behaviors markedly different from the Newtonian response predicted by Stefan's equation [3]. Even in the absence of an electric field, CNC

dispersions deviate from the theoretical $N \propto h^{-3}$ scaling, displaying three distinct quasi-linear regions with slopes that evolve systematically with concentration. These deviations may be attributed to particle agglomeration, localized concentration gradients, and the inability of the viscous carrier fluid to uniformly entrain the particulate phase at small gaps.

Under electric activation, all CNC dispersions show a pronounced rightward shift in the force–distance curves, indicating that the maximum measurable load (20 N) is reached at larger compression gaps. This effect intensifies with increasing CNC concentration. The observed behavior does not conform to the Bingham-based squeeze-flow model typically used for ER fluids [3]. This outcome suggests that field-induced particle deposition and formation of compact columnar structures restricted particle mobility and dominated the mechanical response. These mechanisms lead to compression resistances significantly higher than those predicted from shear-derived yield stresses.

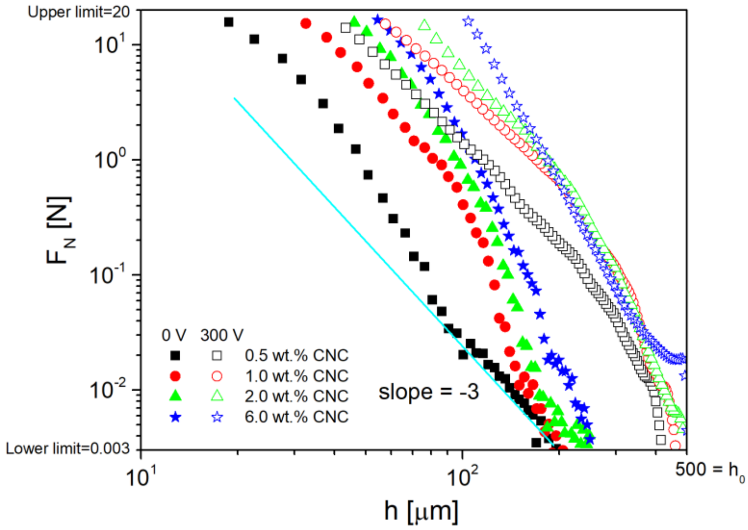


**Fig.1** Evolution with time of the normal force exerted by CNC/castor oil dispersions in squeeze flow tests, as a function of concentration (0.5 to 6 wt.%), in the absence and presence of voltage (0 and 300 V).

## 4. Conclusions

Overall, the results demonstrate that electro-activation substantially enhances the load-carrying capacity of these ER biolubricants, particularly within the 0.5–1 wt.% CNC concentration range where a notable transition in behavior occurs. These findings support the potential of sustainable, electro-responsive lubricants as active components capable of modulating compression resistance and enhancing film thickness under applied electric fields.


***References***

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