

Nanocellulose Exfoliation by High Pressure Homogenization

DeBEE HPH Uses Three Forms of Energy to Transform Cellulose Into Nanocellulose.

High-pressure homogenization (HPH) has emerged as one of the most important mechanical techniques for producing nanocellulose, a class of nanoscale materials derived from natural cellulose. Nanocellulose—commonly in the form of cellulose nanofibrils (CNFs) or cellulose nanocrystals (CNCs)—has attracted significant attention due to its exceptional mechanical strength, biodegradability, and high surface area. Among the various production methods available, HPH stands out as a scalable, solvent-free, and efficient process capable of transforming bulk cellulose fibers into nanoscale structures.

At its core, high-pressure homogenization is a process in which a fluid suspension is forced through a narrow valve or orifice at extremely high pressures, typically ranging from 7,000 to 30,000 psi (50 to 2000 MPa). As the cellulose slurry passes through this constricted space, it experiences intense shear forces, turbulence, cavitation, and rapid pressure drops. These combined mechanical forces act to break down the hierarchical structure of cellulose fibers, progressively reducing them from micron-scale bundles into nanoscale fibrils.

The production of nanocellulose using HPH generally begins with a pretreatment stage. Raw lignocellulosic biomass—such as wood pulp, agricultural residues, or plant fibers—contains cellulose embedded within a matrix of lignin and hemicellulose. To facilitate efficient fibrillation, these non-cellulosic components are partially removed using chemical (e.g., alkaline treatment, bleaching), enzymatic, or physical methods. Pretreatment reduces fiber rigidity, increases accessibility, and lowers the energy required during homogenization.

Once pretreated, the cellulose is dispersed in water to form a slurry and subjected to multiple passes through the high-pressure homogenizer. During each pass, the material is accelerated to high velocities and forced through the high energy zone. The rapid acceleration and deceleration generate shear and impact forces that



DB2000 Production Model

disrupt cellulose microfibrils. This results in the progressive peeling and splitting of fibers into finer fibril.

A key mechanism underlying this transformation is fibrillation—the process by which larger cellulose fibers are delaminated into nanoscale fibrils. Over successive passes, the diameter of the fibrils can be reduced to the nanometer range, typically between 20 and 100 nm, depending on processing conditions.

The number of homogenization passes and the applied pressure are critical parameters that influence the quality and characteristics of the resulting nanocellulose. Higher pressures and more passes generally lead to finer fibrils and more uniform suspensions, but they also increase energy consumption. For example, studies have shown that operating at pressures around 20,000 psi (138 MPa) with multiple passes can yield

nanofibrils with diameters as small as 3–7 nm and relatively high crystallinity. However, excessive processing can lead to degradation of the cellulose structure or unnecessary energy expenditure, making process optimization essential.

One of the major advantages of HPH is its ability to preserve the intrinsic crystalline structure of cellulose while selectively breaking down amorphous regions. This results in nanocellulose with high crystallinity and excellent mechanical properties. Additionally, the process produces stable aqueous suspensions of nanocellulose with desirable rheological behavior, such as high viscosity and shear-thinning properties, which are valuable in applications like coatings, composites, and food systems.

Another important aspect of HPH is its scalability. Unlike some chemical methods that involve hazardous reagents and generate significant waste, high-pressure homogenization is considered an environmentally friendly approach. It does not require solvents and can be scaled from laboratory to industrial production. Industrial homogenizers are capable of operating at pressures up to tens of thousands of psi (over 300 MPa) and can process large volumes of material continuously. This makes HPH particularly attractive for commercial nanocellulose production.

Despite these advantages, HPH is not without its challenges. The process is energy-intensive, especially when applied to untreated or poorly pretreated biomass. High energy consumption can increase production costs and limit sustainability if not properly managed. To address this, researchers often combine HPH with pretreatment techniques such as enzymatic hydrolysis, 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO)-mediated oxidation, or ultrasonication. These methods weaken the fiber structure before homogenization, significantly reducing the energy required to achieve nanoscale fibrillation.

In addition, clogging of the homogenizer can occur when processing high-solid-content suspensions or insufficiently refined fibers. This necessitates careful control of feed consistency and particle size prior to homogenization. Equipment wear is another consideration, as the extreme pressures and mechanical stresses can lead to maintenance challenges over time.

The versatility of HPH-produced nanocellulose has led to a wide range of applications. In materials science, nanocellulose is used as a reinforcing agent in polymer composites, improving strength and reducing weight. In the food industry, it functions as a stabilizer, thickener, and texture modifier. In biomedical applications, its biocompatibility and high surface area make it suitable for drug delivery systems, wound dressings, and tissue

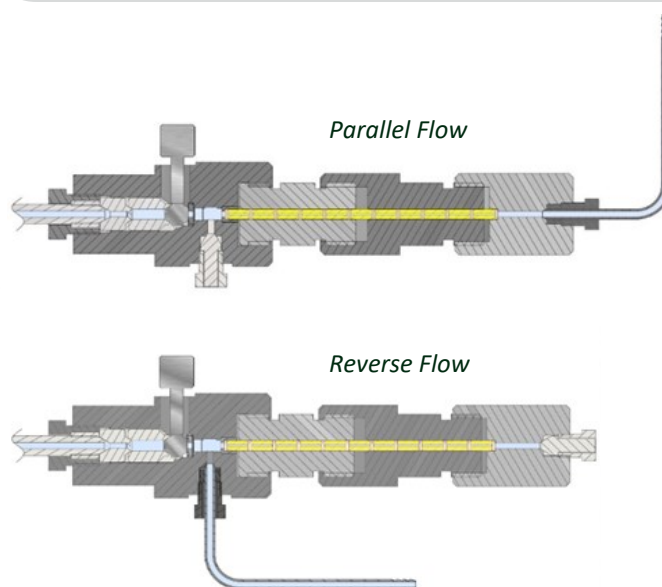
engineering scaffolds. The ability to tailor nanocellulose properties through controlled homogenization further enhances its utility across these fields.

HPH is a widely used mechanical step in nanocellulose production, and its effectiveness has been demonstrated in laboratory-scale studies using systems such as the Mini DeBEE. In one study, chemically modified cellulose was processed using a Mini DeBEE HPH¹ at approximately 30,000 psi (205 MPa) for multiple passes to successfully produce nanocellulose, highlighting the role of controlled mechanical disintegration in fibrillation processes.

Pion DeBEE technology uses a unique high energy zone, the Emulsifying Cell (EC), that uses fixed geometry and exchangeable elements, to allow optimization of the forces involved in fibrillation. DeBEE HPH can reach 45,000 psi (310 MPa), providing energy beyond conventional HPH systems. The customizable configuration of the EC enables creation of many varieties of nanocellulose materials. The EC can be easily disassembled by the user to clear plugs if they occur during process development. Wear components can be easily and inexpensively replaced by the operator, in contrast to the expensive and time-consuming replacement of Interaction Chambers and homogenizer valves used in other HPH systems.

DeBEE uHPH enables optimization of cellulose processing using the following variables.

- Flow Patterns** – Parallel Flow, Reverse Flow, Dual Feed
- Absorption Cell Patterns** – Number and Size of Reactors
- Operating Pressure (psi/Bar) & Back Pressure (psi/Bar)**
- Nozzles Sizes** – Range from 0.1mm - 0.25mm



Dual Feed

- A second in-feed option is available with DeBEE technology. This introduces the possibility of separating the ingredients of a formulation. There are several opportunities created by this configuration
- Ingredients that either need to avoid the highest energy zone, or don't require it, can be input after the nozzle, avoiding some of the shear and cavitation. These ingredients are still efficiently mixed into the stream as they pass through the reactor sequence.
- Sometimes ingredients should not be combined until they can be mixed with high energy. The DeBEE Dual Feed option keeps reactive ingredients separated until they can be intimately mixed in milliliter quantities. This avoids premature reactivity and destabilization of the premix.
- Add polymers, crosslinkers or plasticizers to enhance the properties of the nanocellulose.
- The Dual Feed option can be used to simply increase the throughput capacity of the system.



An example of the Dual Feed option in use on a Nano DeBEE.

Some models allow for certain powders to be incorporated directly into the mixing stream.



In conclusion, high-pressure homogenization is a powerful and widely used method for processing nanocellulose. By applying intense mechanical forces to pretreated cellulose fibers, HPH effectively breaks down the complex fiber structure into nanoscale fibrils with desirable properties. While the process requires careful optimization to balance energy consumption and product quality, its scalability, environmental friendliness, and versatility make it a cornerstone technology in the production of nanocellulose. As research continues to advance, improvements in pretreatment strategies and homogenization efficiency are likely to further enhance the feasibility and sustainability of this important process. The DeBEE design provides the flexibility and enhanced performance capabilities, and the practical operational mechanics to make this a successful R&D and commercial application.

Reference

¹ Nanocellulose Life Cycle Assessment, ACS Sustainable Chem. Eng. 2013, 1, 919–928

[Nanocellulose Life Cycle Assessment, ACS Sustainable... - Google Scholar](#)