



**DSTF**  
DIPARTIMENTO DI SCIENZA E  
TECNOLOGIA DEL FARMACO  
UNIVERSITÀ DEGLI STUDI DI TORINO



**UNIVERSITÀ  
DI TORINO**



**NANOMATERIALS FOR INDUSTRY  
AND SUSTAINABILITY**



**processes**

an Open Access Journal by MDPI

**PROF. DR. GIANCARLO CRAVOTTO**  
Editor-in-Chief of *Processes*



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# Scaling up new extraction technologies: high-value protein extracts from industrial residues

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**POLITECNICO  
MILANO 1863**

DIPARTIMENTO DI CHIMICA,  
MATERIALI E INGEGNERIA CHIMICA  
GIULIO NATTA

**Milan, October 28<sup>th</sup> 2025**



## **PROTEINS FOR HUMAN CONSUMPTION**

**PROTEINS** per capita range of 45 to 60 g per day the requirement spans  
**about 133 to 177 million ton/year**

## **PROTEINS FOR ANIMALS FEEDING**

Total protein meals about **366 million ton/year**

## **PROTEINS FOR MATERIALS**

Global soybean production c.ca **350 million metric tonnes** in 2022

The gelatin production **c.ca 470,000 ton/year** gives a concrete volume for a protein-derived  
polymeric material

## INDUSTRIAL PROTEIN SOURCES



Soy



Yellow Pea



Rice



Wheat



Hemp



Lentils

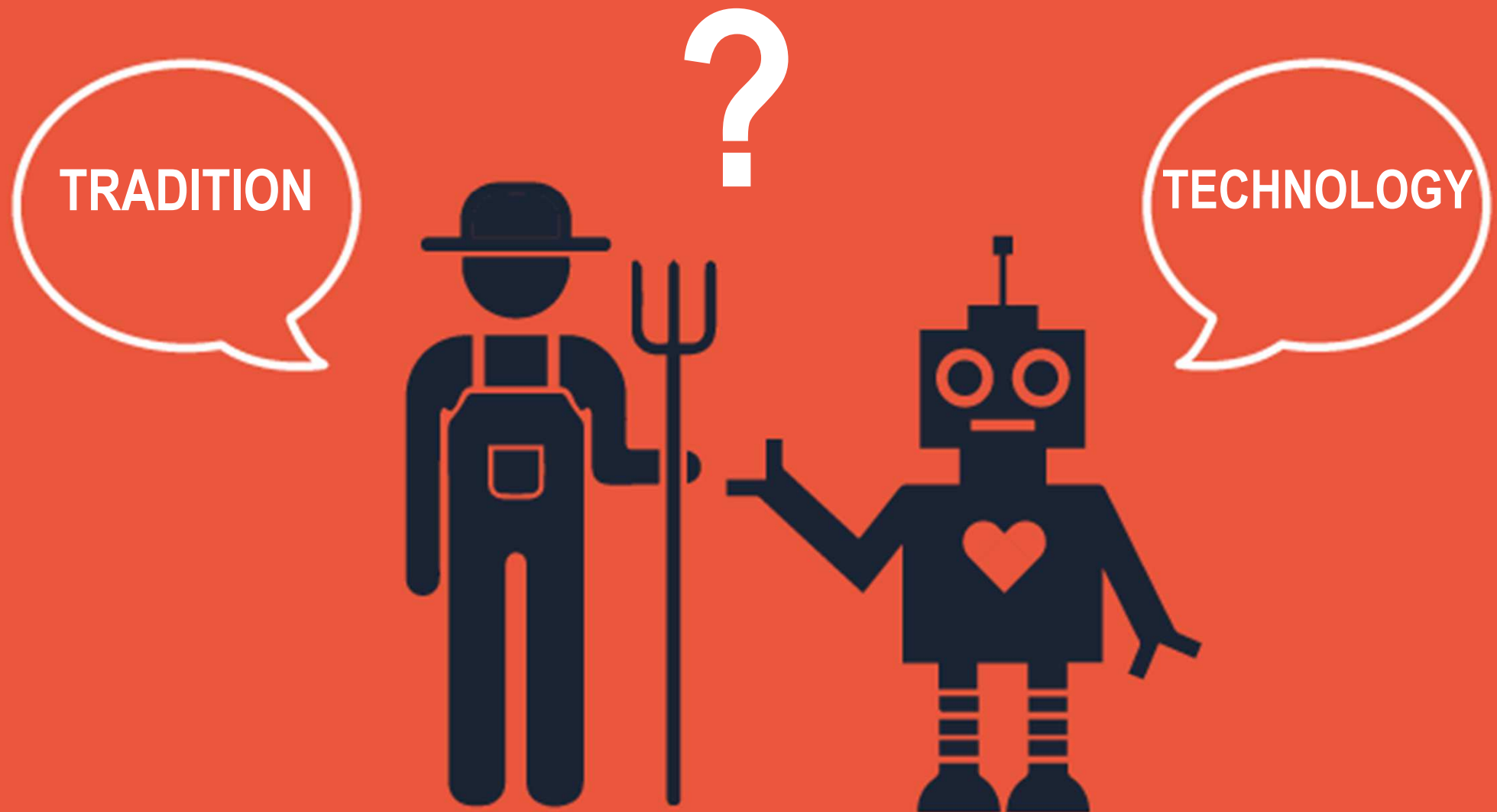


Fava Bean



Chickpea

**Broken/split beans** (defect tolerance):  
typical limits are **about 2-4 %** for top grades and **up to 8 %** for lower grades





# **SOCIETAL BARRIERS** **... the bottleneck**

## **Cultural**

Lacking awareness and/or willingness to engage with the circular economy

## **Regulatory**

Lacking policies that support a circular economy transition

## **Market**

Lacking economic viability of circular economy business models

## **Technological**

Lacking (proven) technologies to implement CE





## PILOT SCALE TECHNOLOGY PLATFORM

EXTRACTION  
PROCESSING

DOWNSTREAM

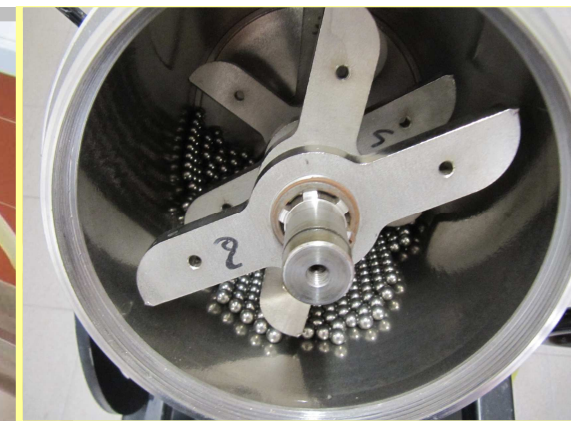
PURIFICATION  
DRYING

## SEMI-INDUSTRIAL APPLICATIONS

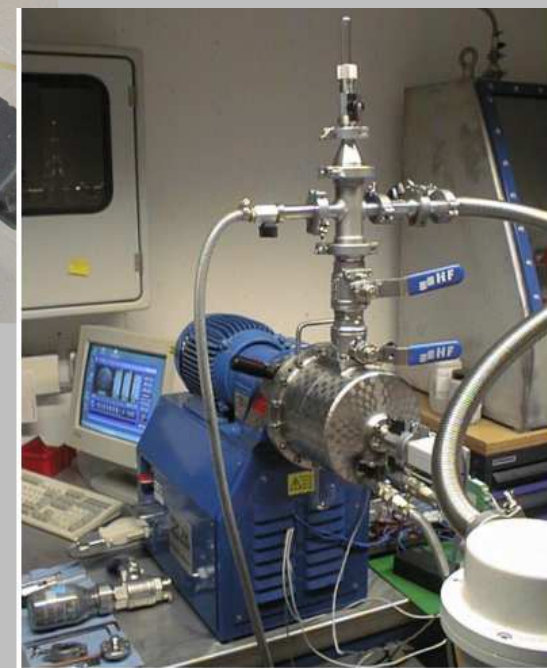




ROW MATERIAL  
BYPRODUCTS  
PRETREATMENTS



## MECHANOCHEMICAL TREATMENTS





# Solid / Solid Separation





# Solid / Solid Separation



**wheat bran**



**whole wheat flour**

# Cocoa Bean Shell



GRINDING



CYCLONS AND  
VIBRATING SIEVERS







**GRINDING**



**FLOW MODE  
EXTRACTION**



**ENRICHED FRACTIONS**



**FLOW MODE EXTRACTION**



**SOLID / LIQUID / LIQUID  
SEPARATION**



**FILTRATION**



**CONCENTRATION  
(50 L)**



**ANALYSIS**



# PROTEIN DELIPIDATION





## HEMP SEEDS



## COLD PRESS EXTRACTION









# Ferretting out the secrets of industrial hemp protein as emerging functional food ingredients

## PROTEIN CONTENT

|               |        |
|---------------|--------|
| HEMPSEEDS     | 20–25% |
| HEMPSEED CAKE | 35–50% |
| DEHULLED SEED | 30–40% |

## AMINO ACIDS PROFILE

Methionine, phenylalanine, arginine, glutamic acid, leucine, isoleucine, valine, threonine, histidine, lysine, cysteine

Tryptophan in little concentration (0.22 g/100 g)

**Hempseed protein mainly consist in globulins and albumins (60–80%)**

**Higher digestibility (61%) when compared to lentil (52%) or whole wheat (40%)**



# CURRENT INDUSTRIAL PRODUCTION



## SEEDS OILS



EPA/635/R-03/012  
[www.epa.gov/iris](http://www.epa.gov/iris)

## TOXICOLOGICAL REVIEW

OF

## n-HEXANE

(CAS No. 110-54-3)

In Support of Summary Information on the  
Integrated Risk Information System (IRIS)

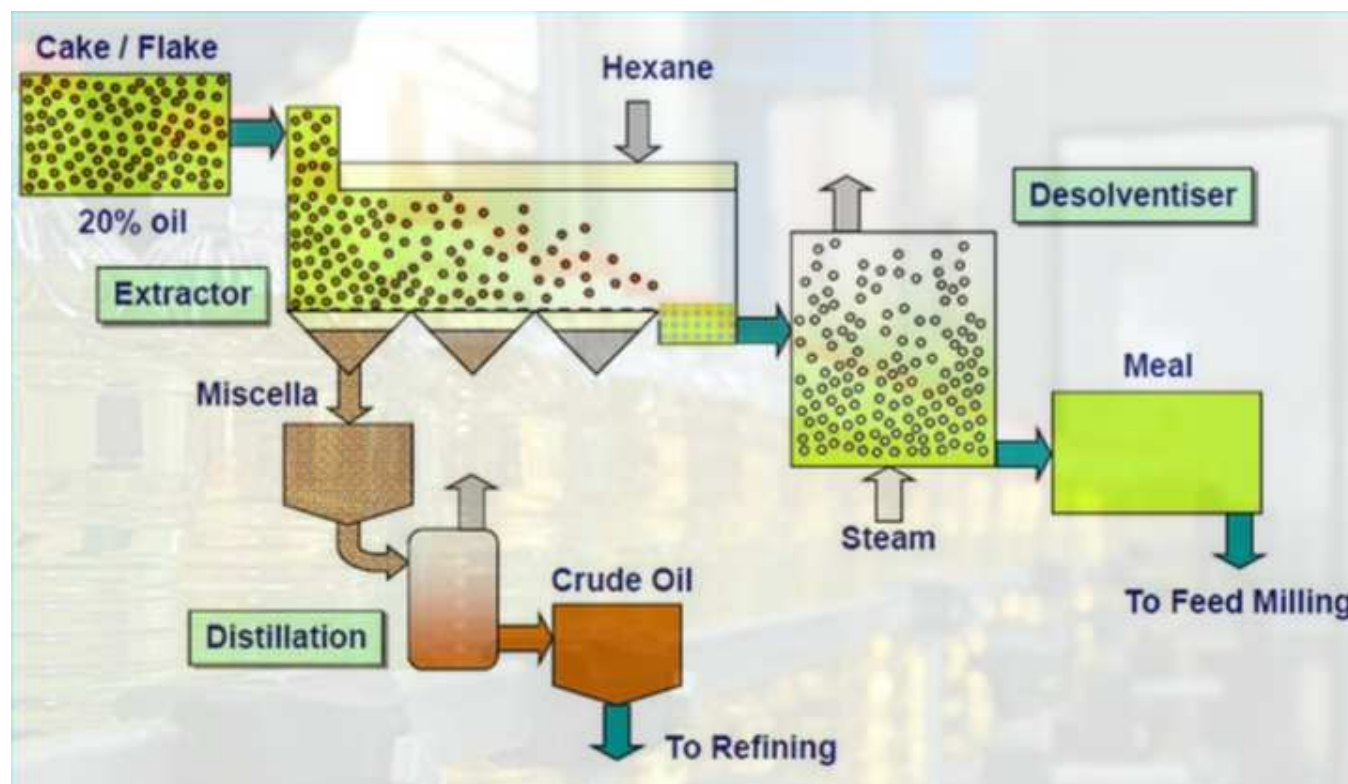
November 2005

U.S. Environmental Protection Agency  
Washington, DC



*Review*

# Towards Substitution of Hexane as Extraction Solvent of Food Products and Ingredients with No Regrets

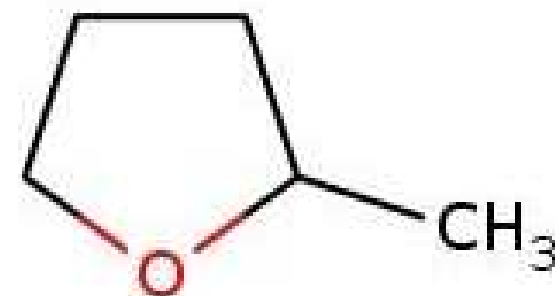




ADOPTED: 26 January 2022

## SCIENTIFIC OPINION

# Safety assessment of 2-methyloxolane as a food extraction solvent



# DIRECTIVES

## COMMISSION DIRECTIVE (EU) 2023/175

of 26 January 2023

**amending Directive 2009/32/EC of the European Parliament and of the Council as regards  
2-methyloxolane**

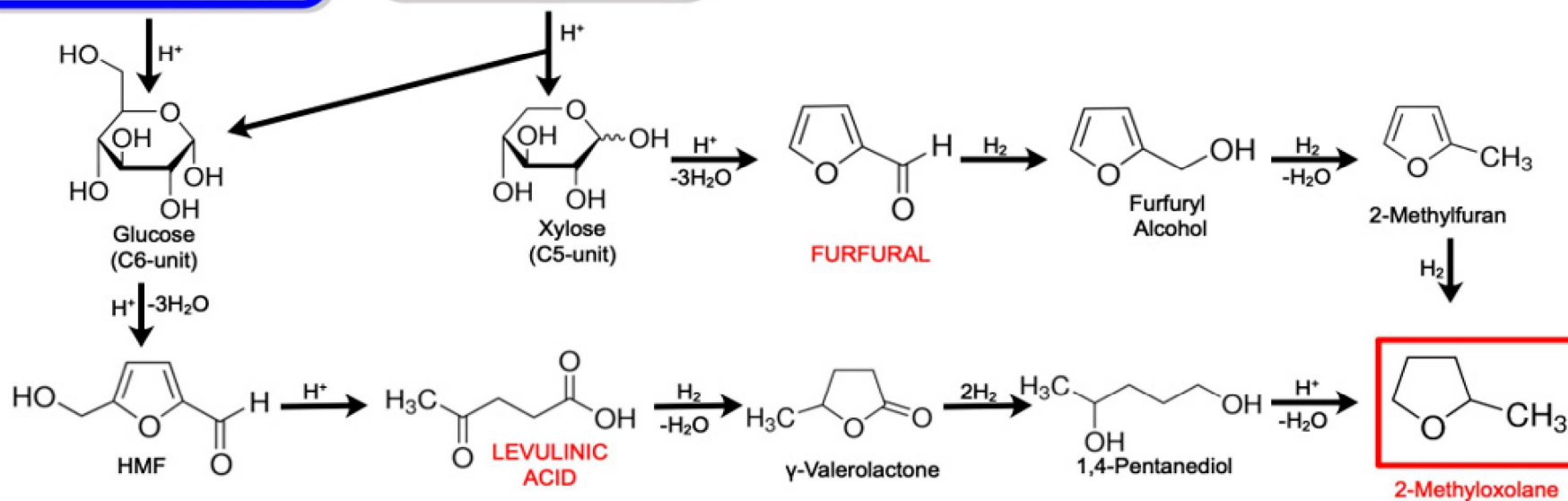
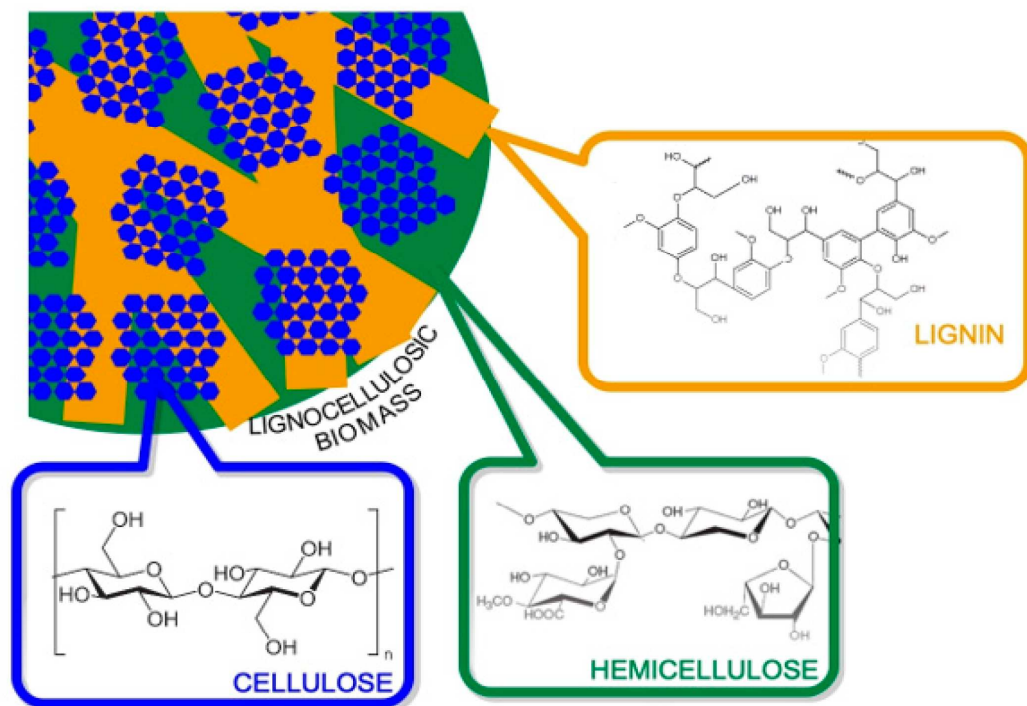
- (4) Therefore, it is appropriate to authorise the use of 2-methyloxolane as an extraction solvent in the production or fractionation of fats, oils or cocoa butter, in the preparation of defatted protein products, defatted flours, preparation of defatted cereal germs and flavourings from natural flavouring materials. It is also appropriate to establish specific purity criteria for 2-methyloxolane.

*For the Commission*  
*The President*

Done at Brussels, 26 January 2023.

Ursula VON DER LEYEN

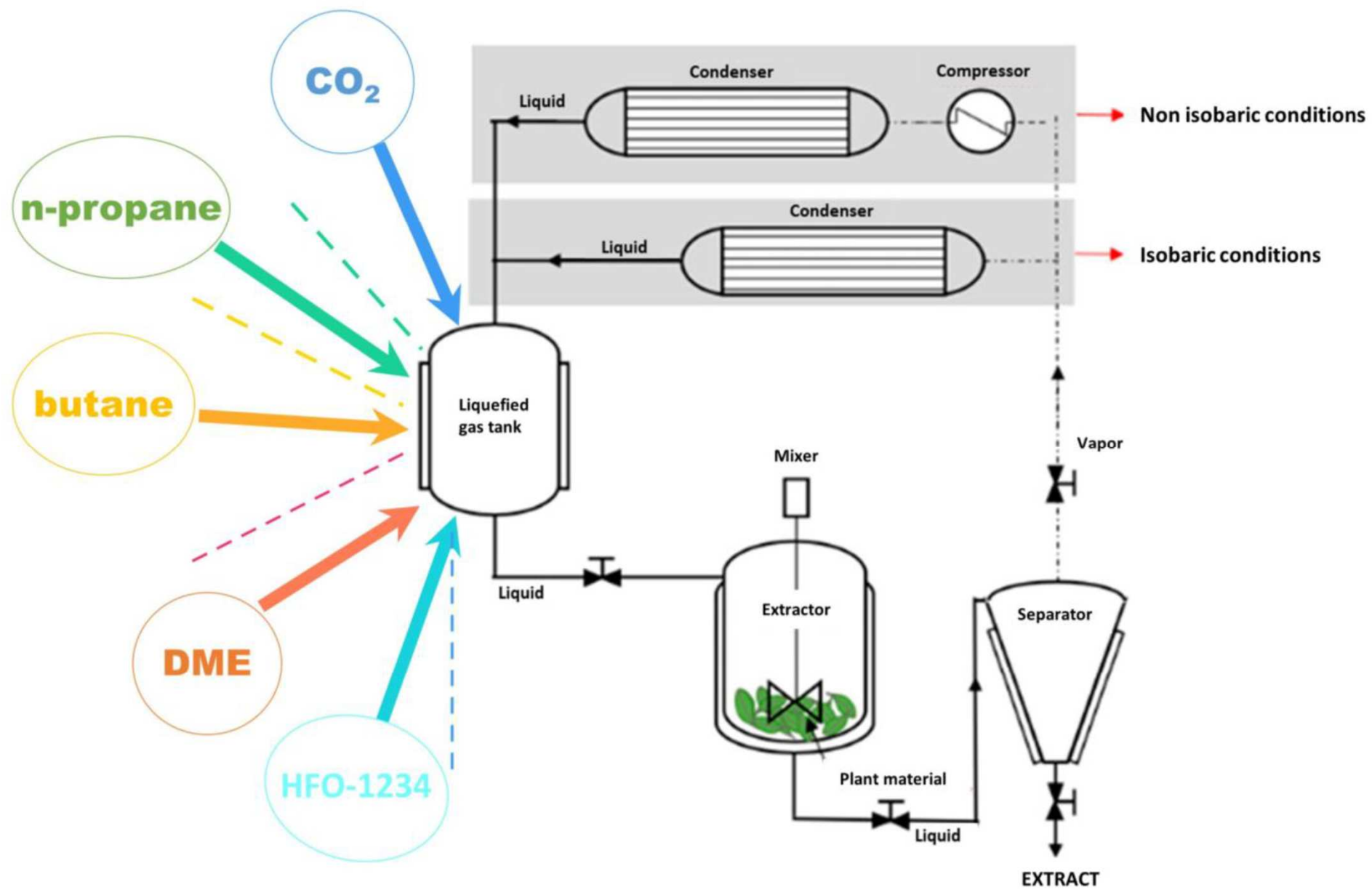




Sc-CO<sub>2</sub> and  
liquefied gases







## LIQUID BUTANE EXTRACTION



LWT - Food Science and Technology 85 (2017) 524–533

An original approach for lipophilic natural products extraction: Use of liquefied *n*-butane as alternative solvent to *n*-hexane

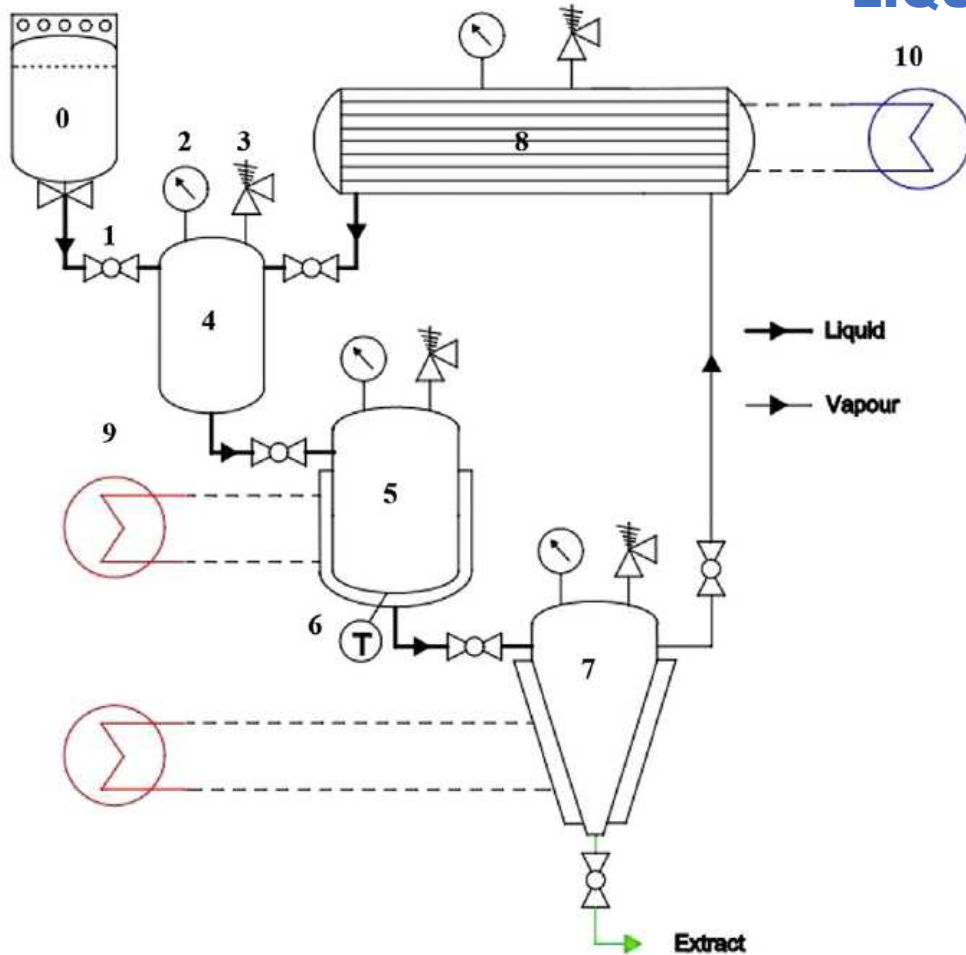




Solvay 10 08 2021



## LIQUID BUTANE EXTRACTION NECTACEL®



0. n-butane bottle; 1. valve; 2. manometer; 3. safety valve; 4. solvent storage tank;  
5, double jacketed stainless extractor; 6. thermometer; 7. double jacketed stainless evaporator;  
8. stainless condenser; 9. Heated bath circulator; 10, Cooling bath circulator















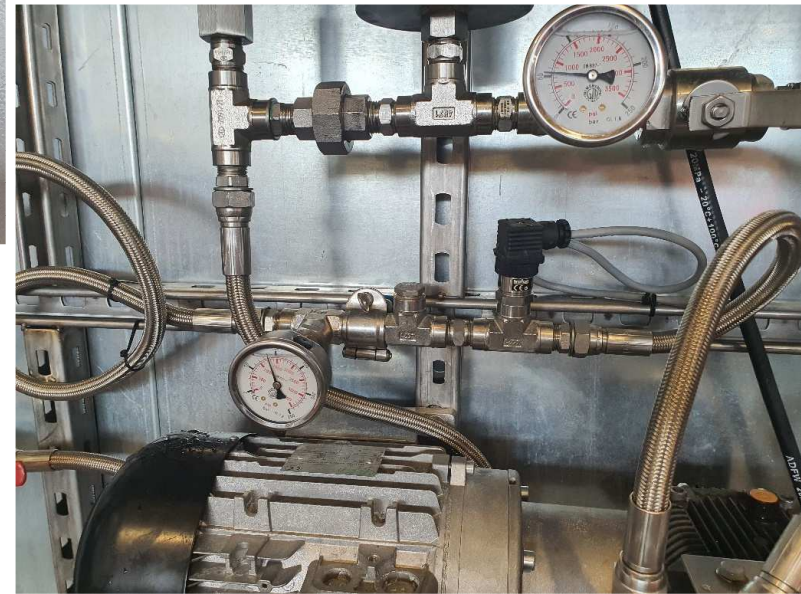
# Highly-Efficient Caffeine Recovery from Green Coffee Beans under Ultrasound-Assisted SC-CO<sub>2</sub> Extraction

 *processes*

2020, 8, 1062







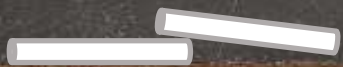


**SEMI-INDUSTRIAL  
ULTRASOUND SC-CO<sub>2</sub>**

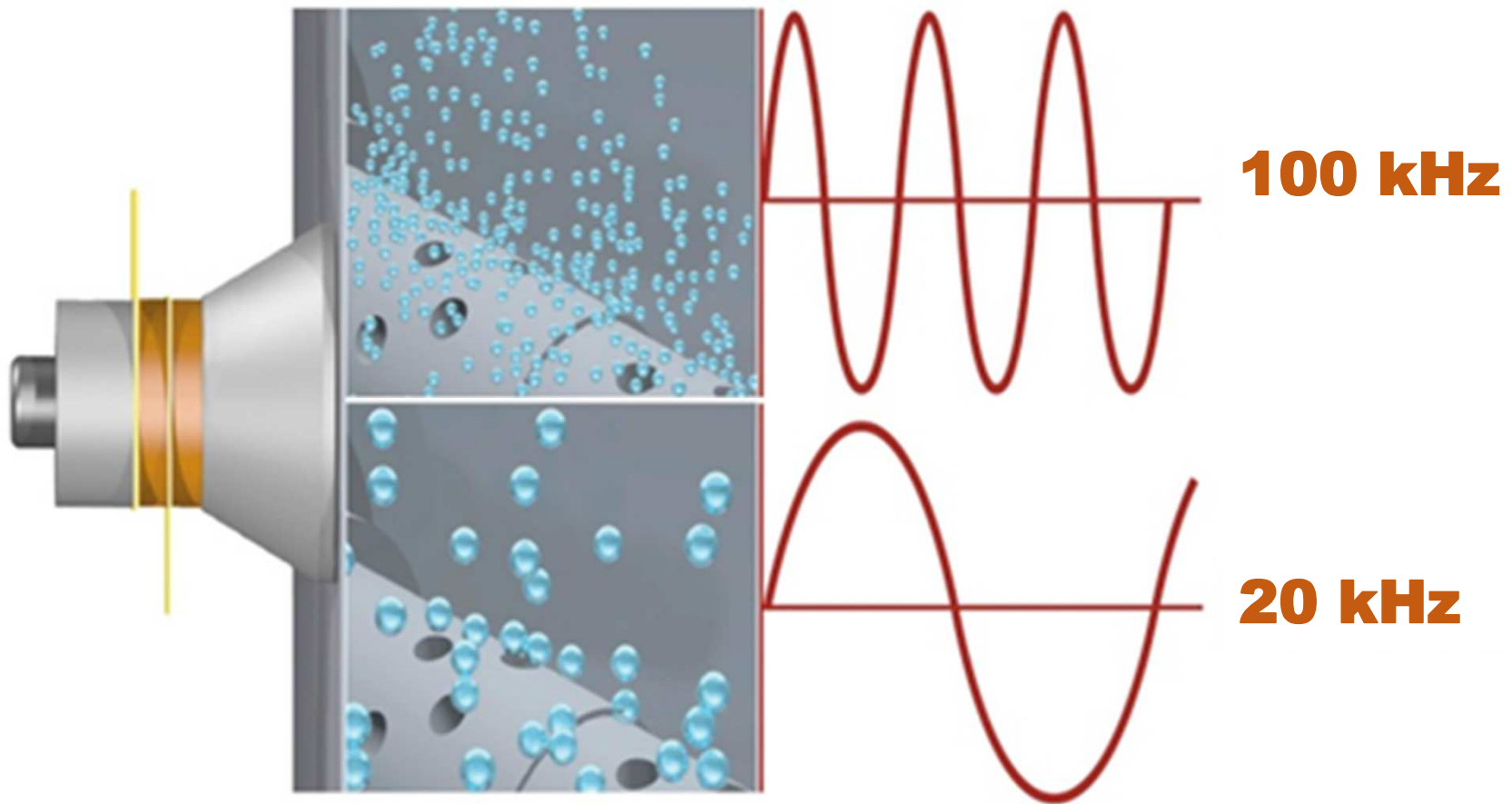




# ULTRASOUND- ASSISTED EXTRACTION



# ACOUSTIC CAVITATION

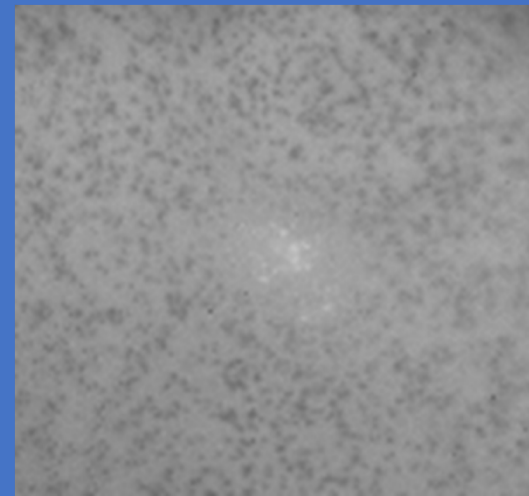
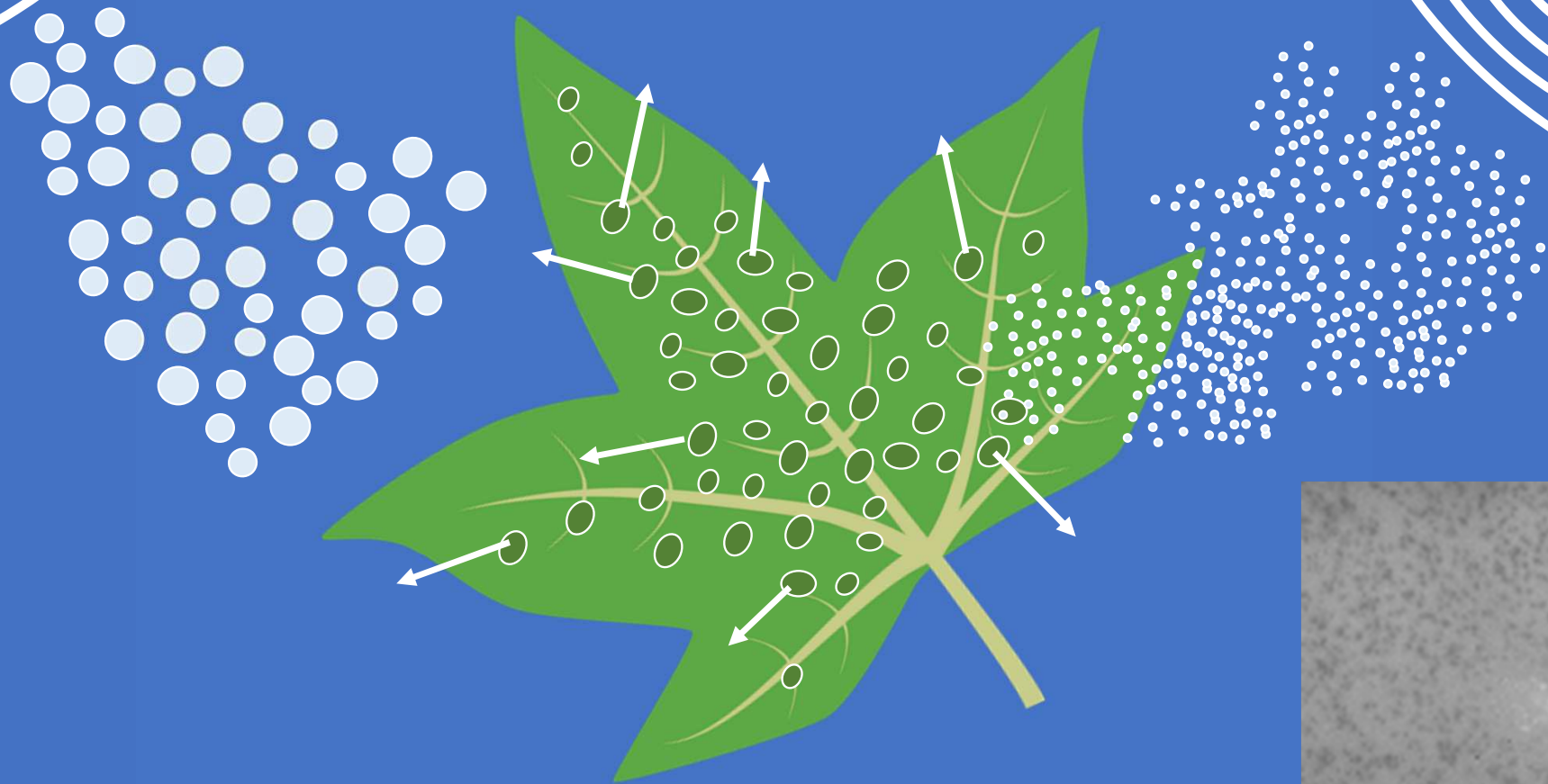




ULTRASOUND  
20 kHz

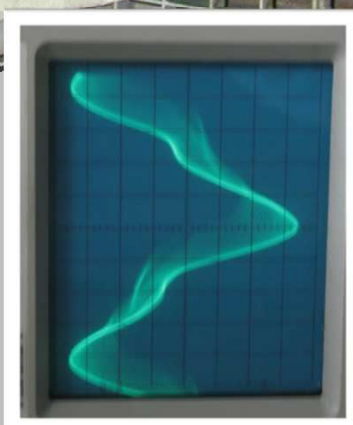
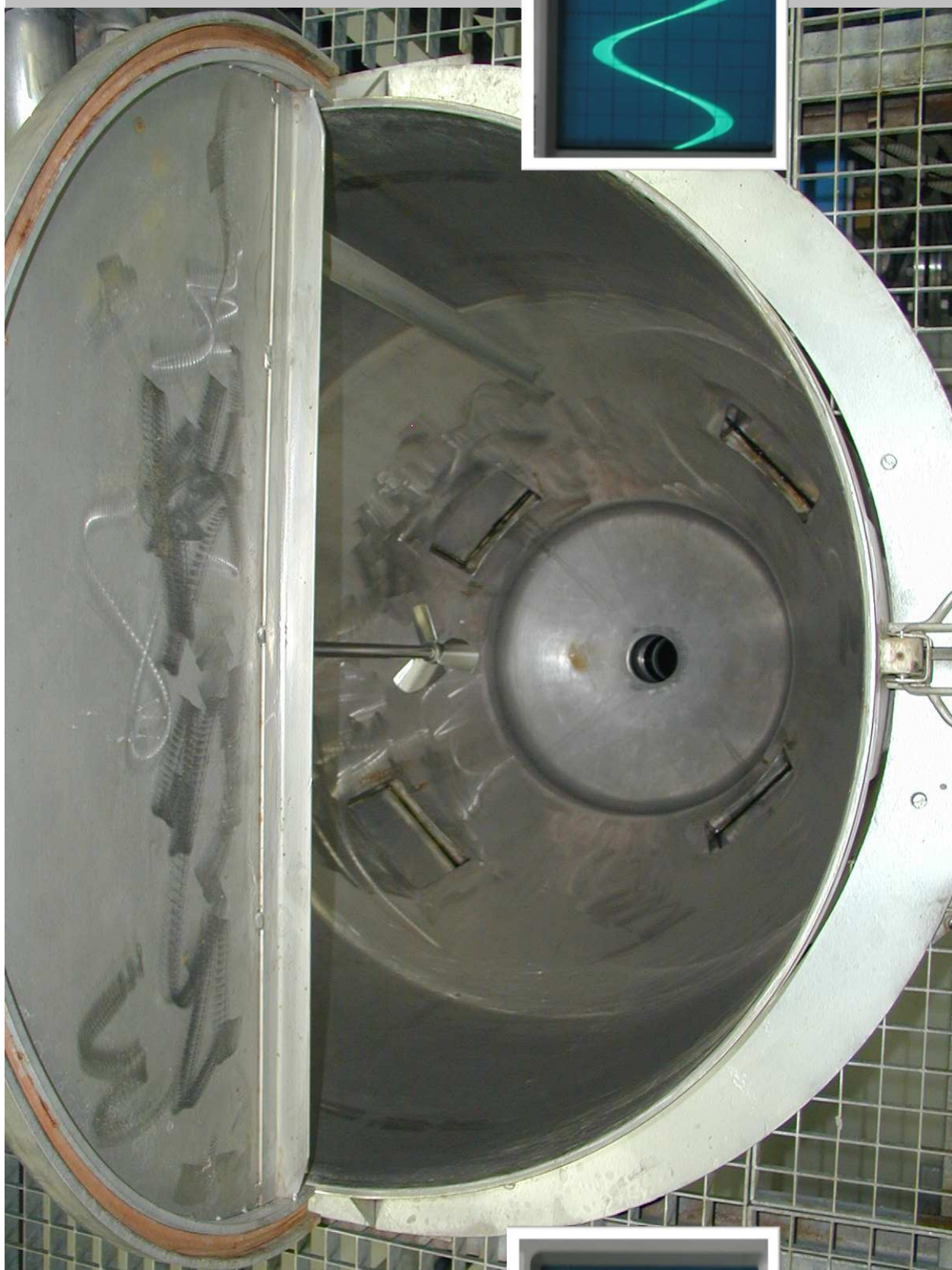
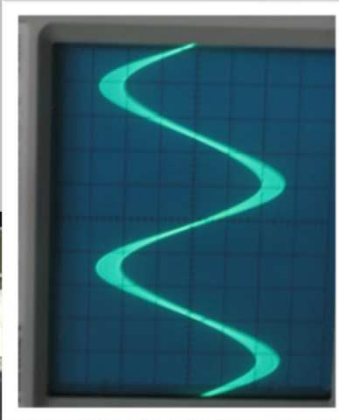
## ULTRASOUND-ASSISTED EXTRACTION

ULTRASOUND  
80 kHz

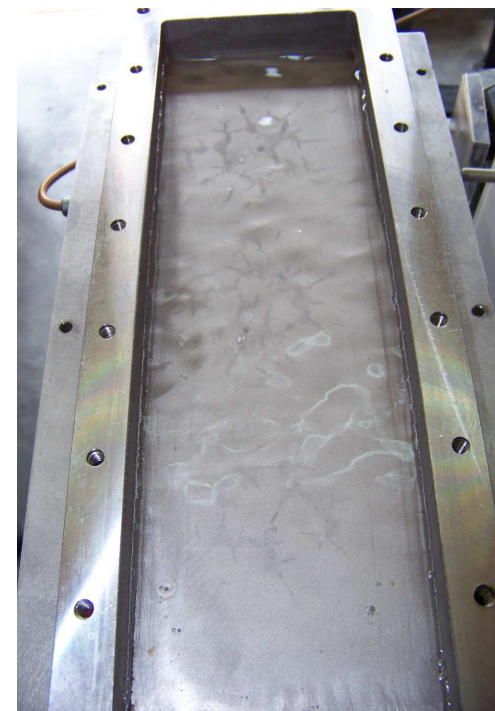
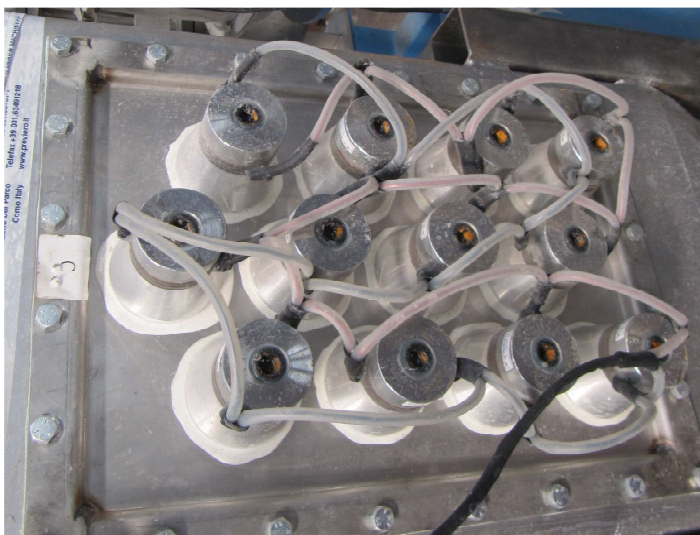




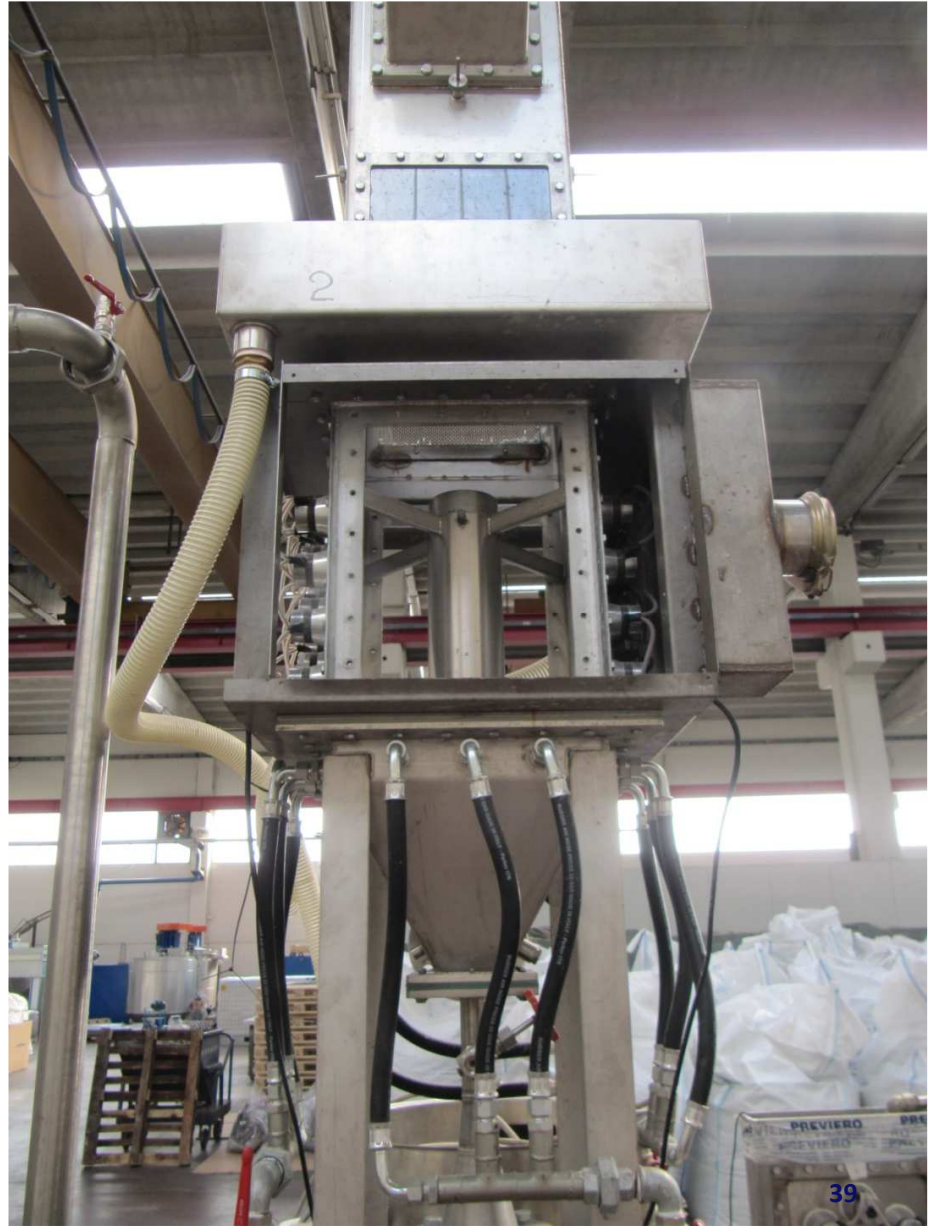
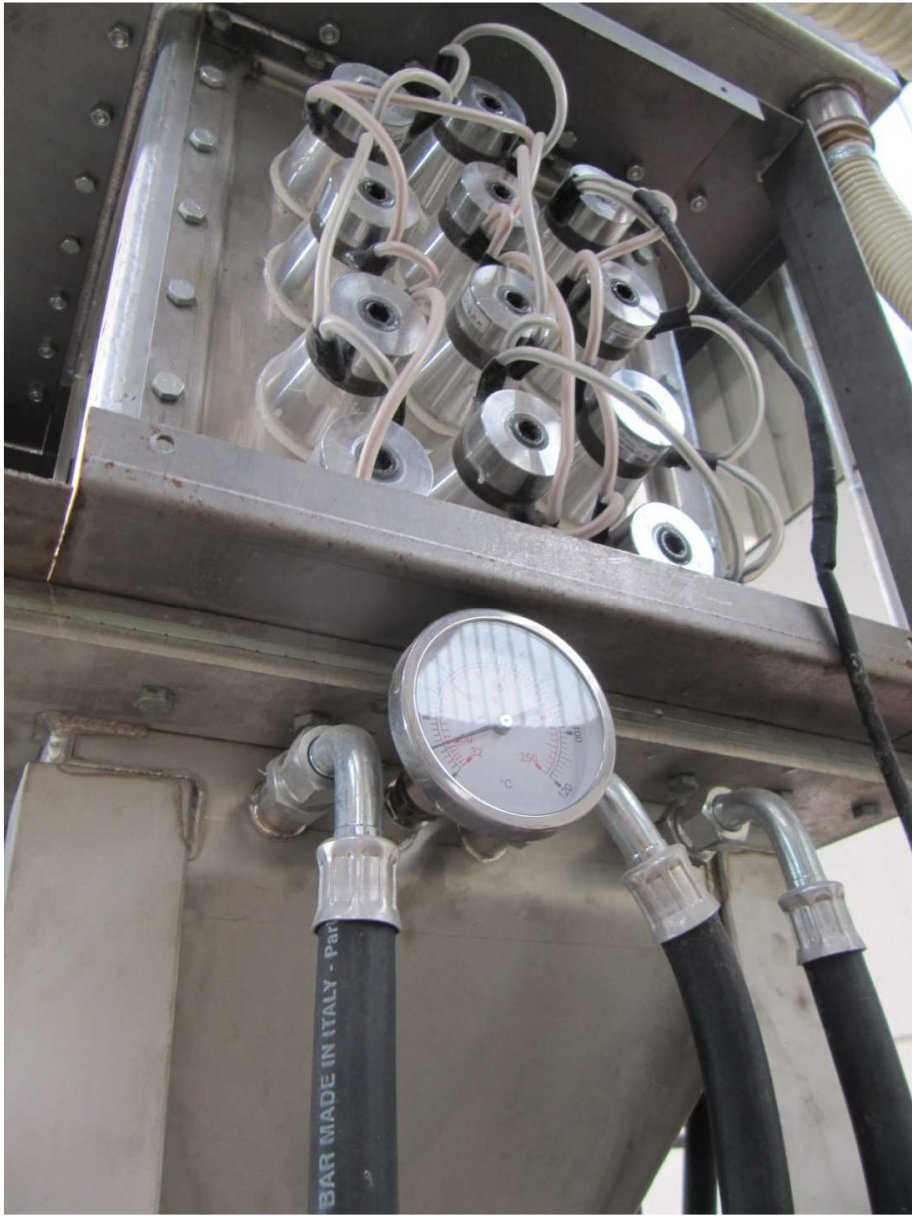


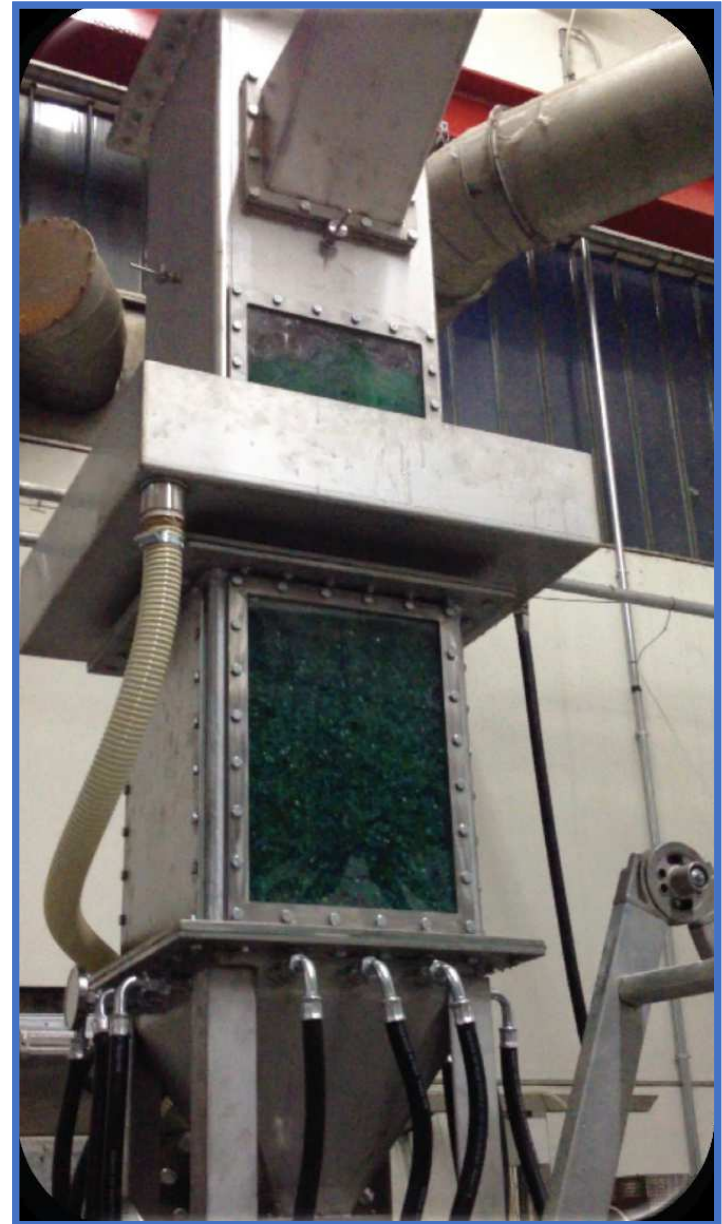
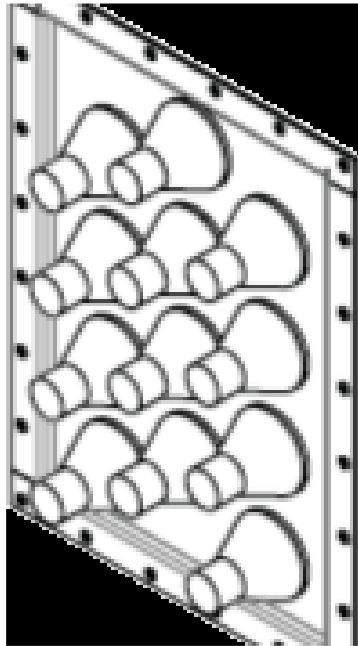
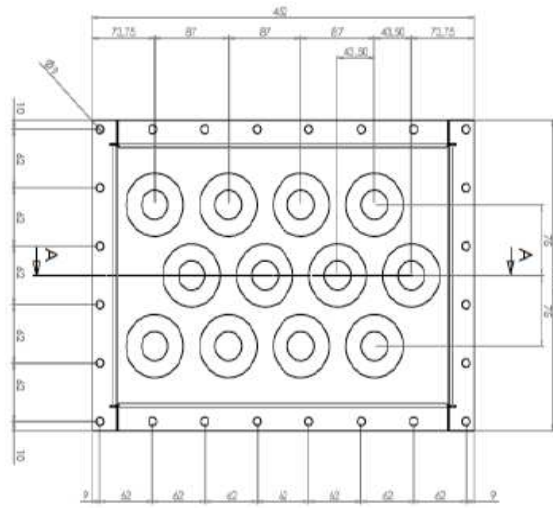






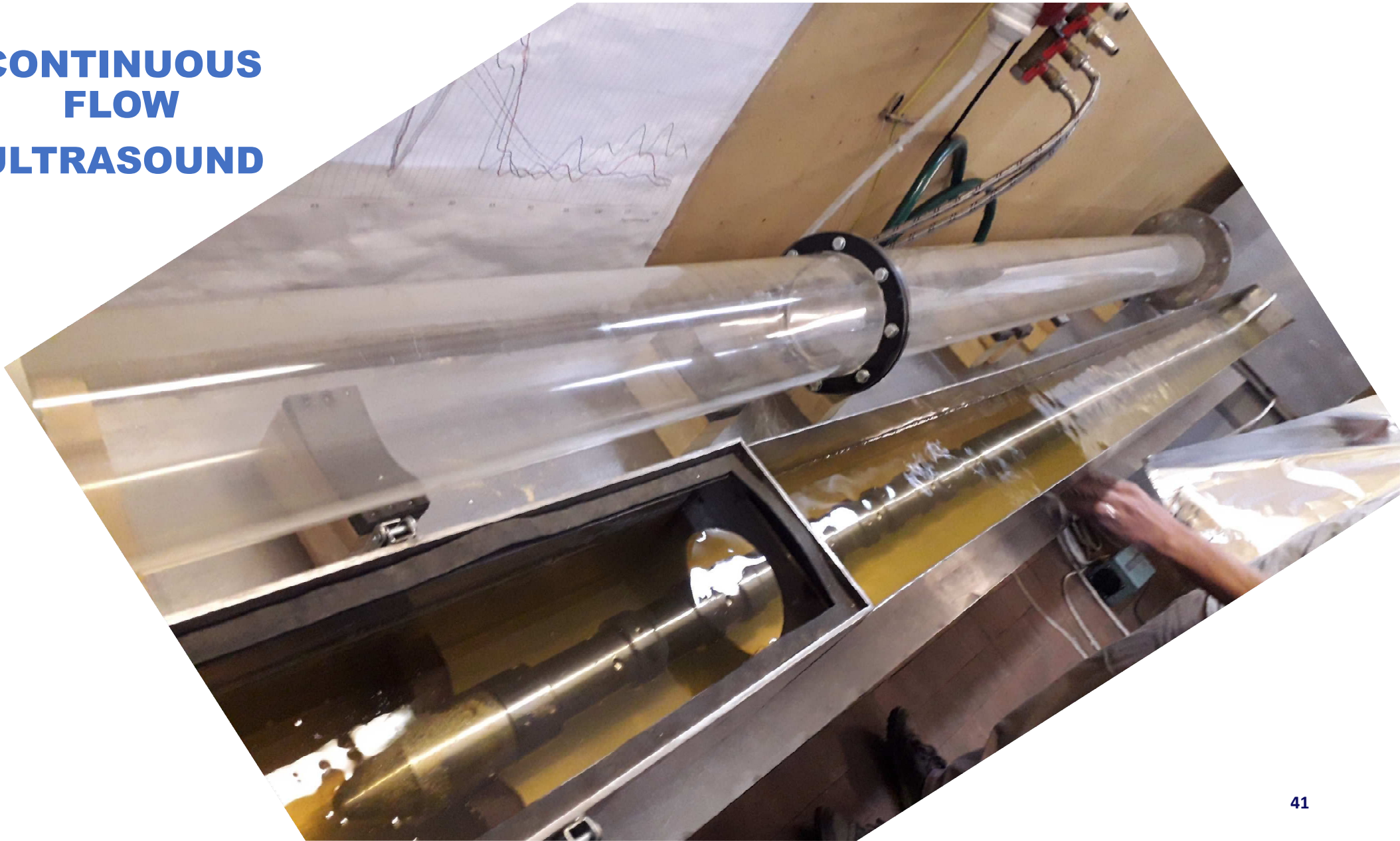








# **CONTINUOUS FLOW ULTRASOUND**



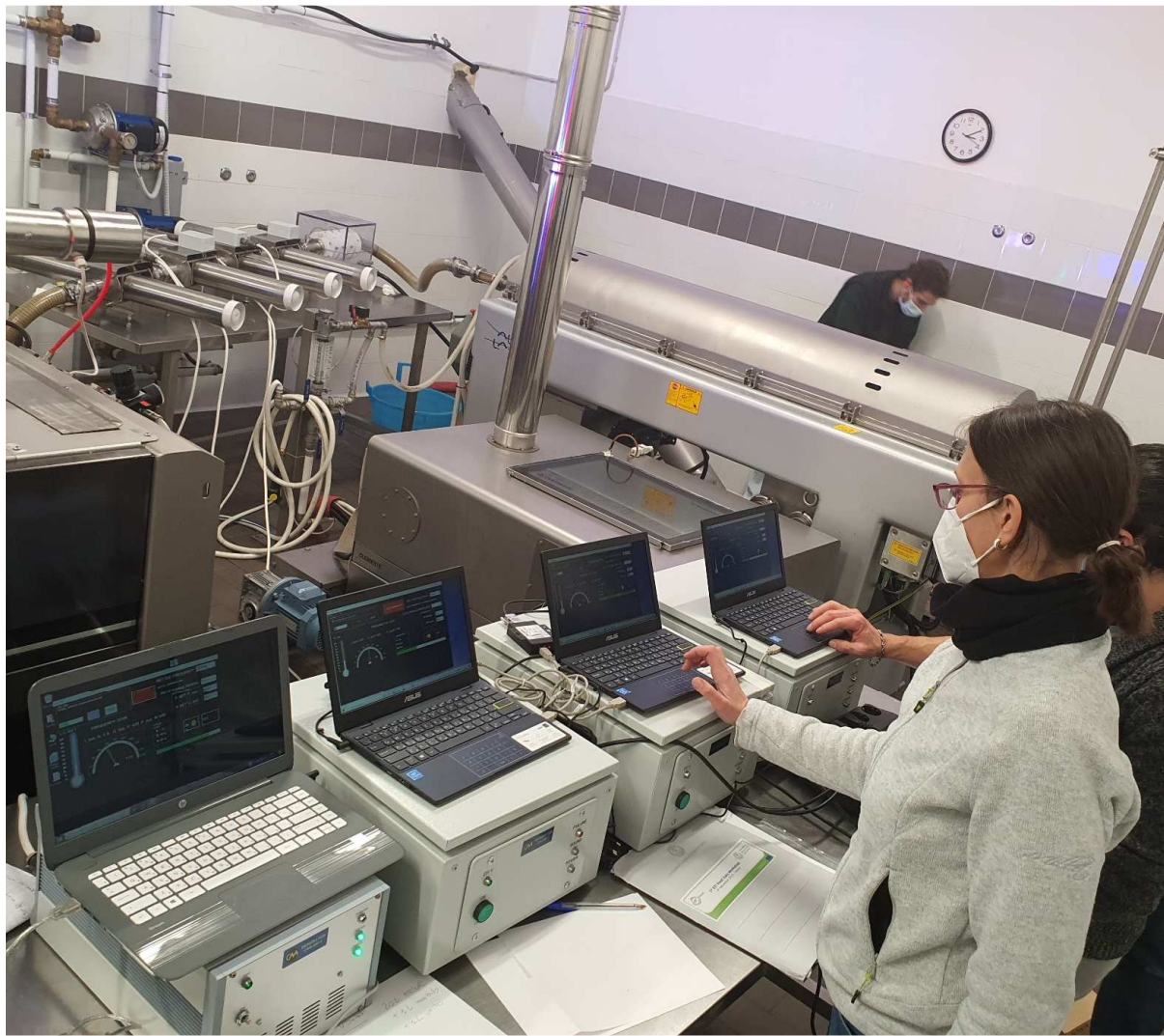




## ULTRASONIC FLOW REACTOR TWO MODULES - 3 KW - 25 kHz

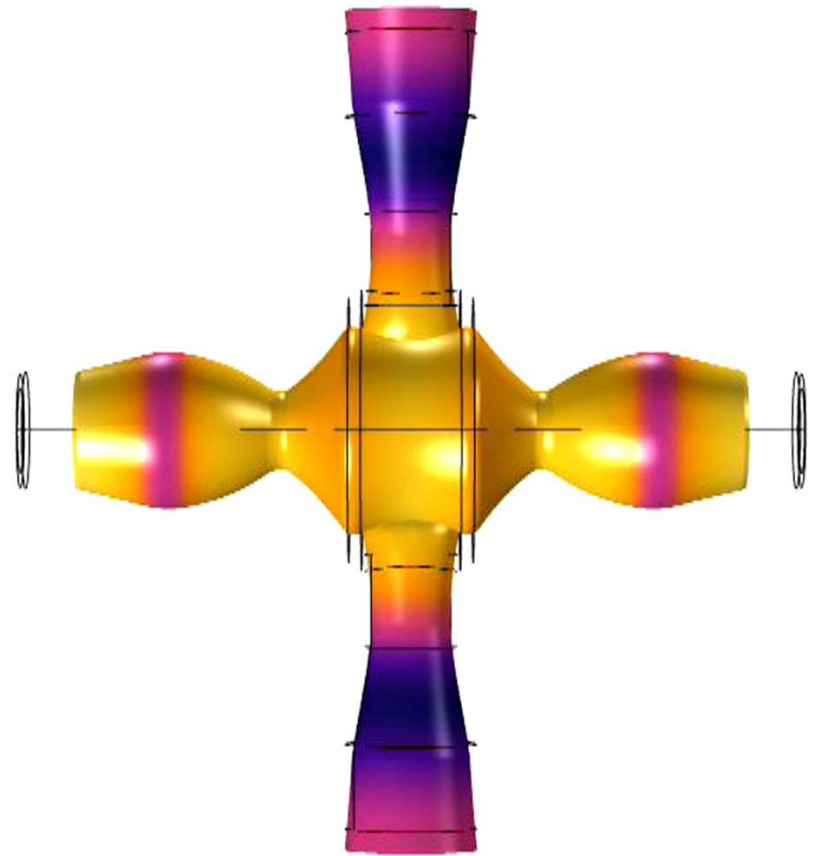




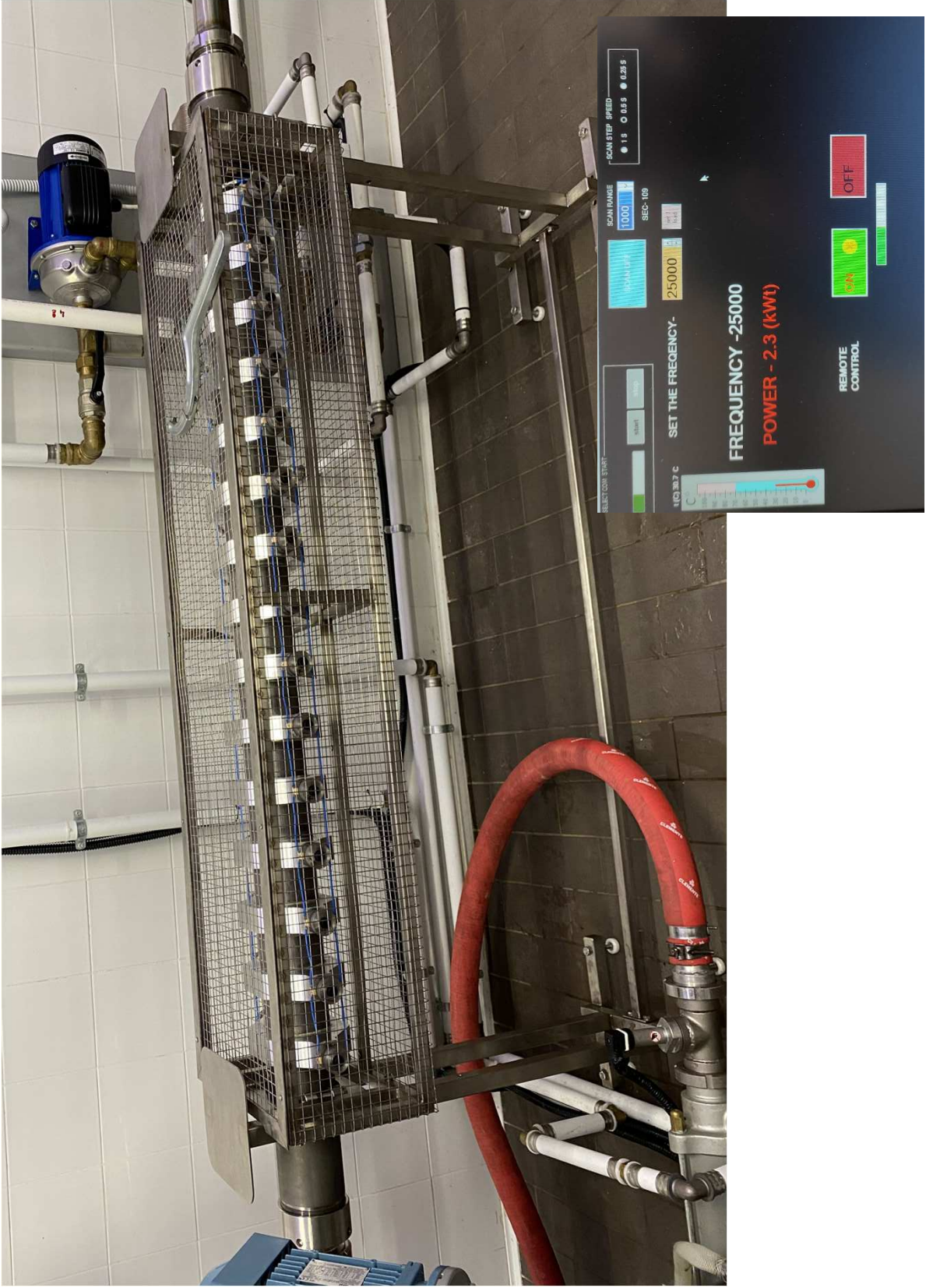
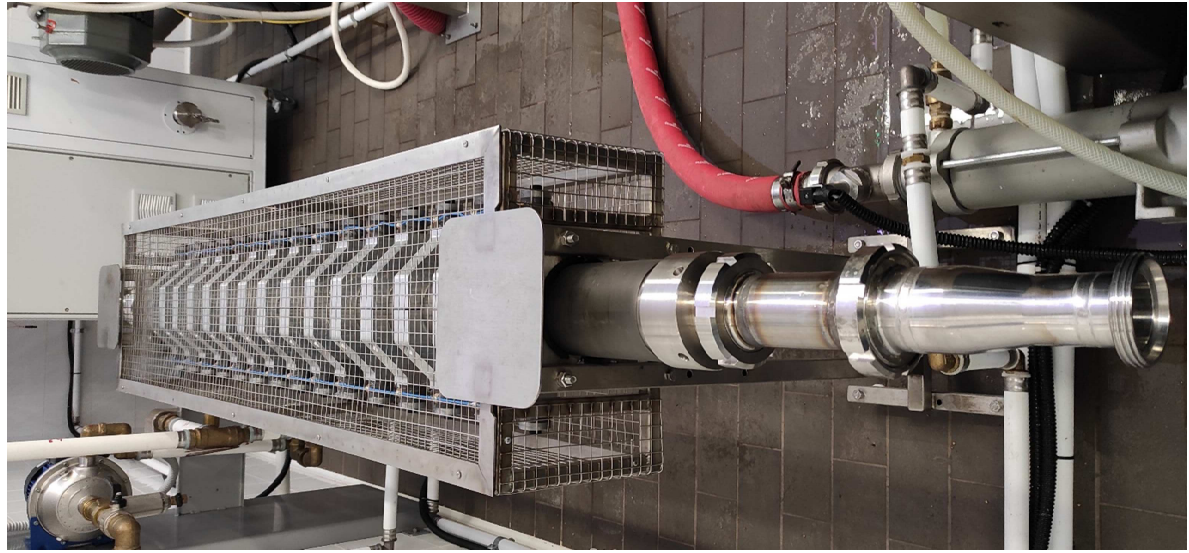




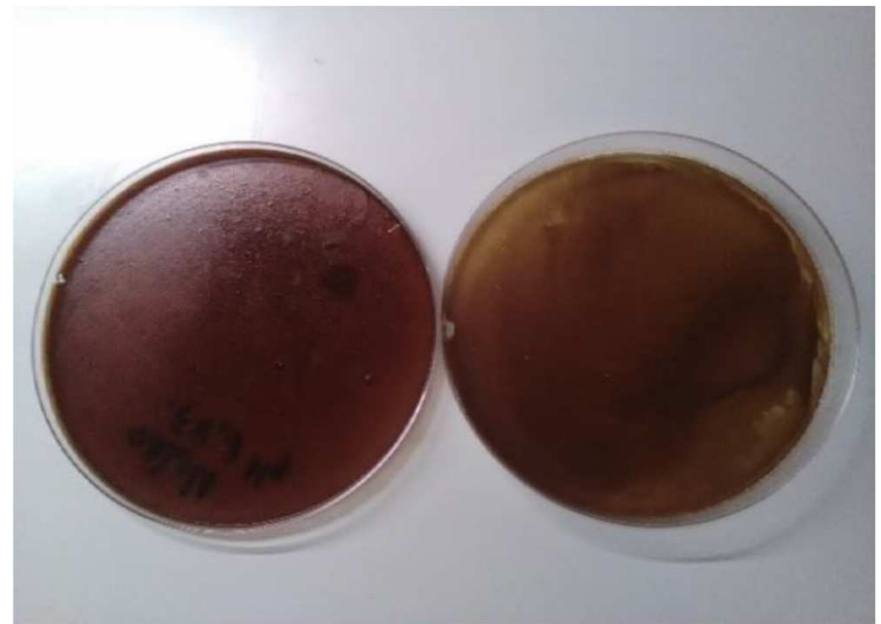








## Milk Protein Polymer







HIGH-SHEAR  
HOMOGENIZER

HYDRODYNAMIC  
CAVITATION UNITS

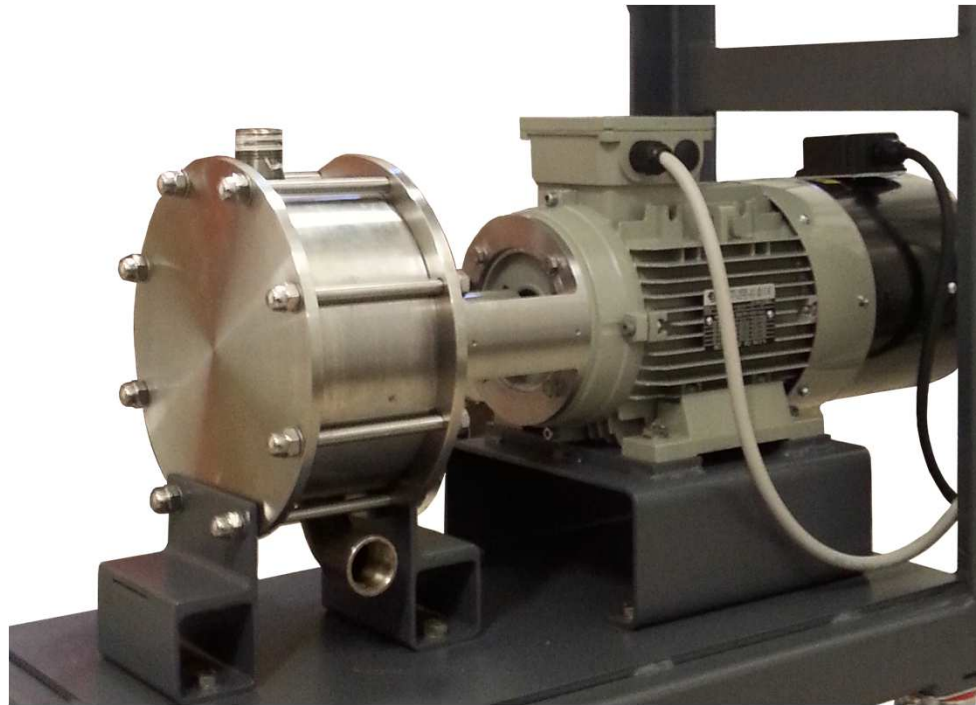
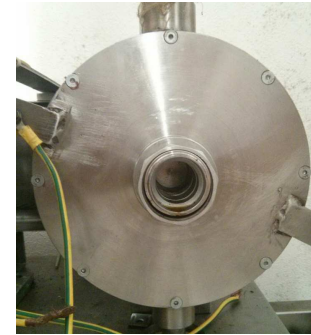




# HIGH-SHEAR HOMOGENIZERS

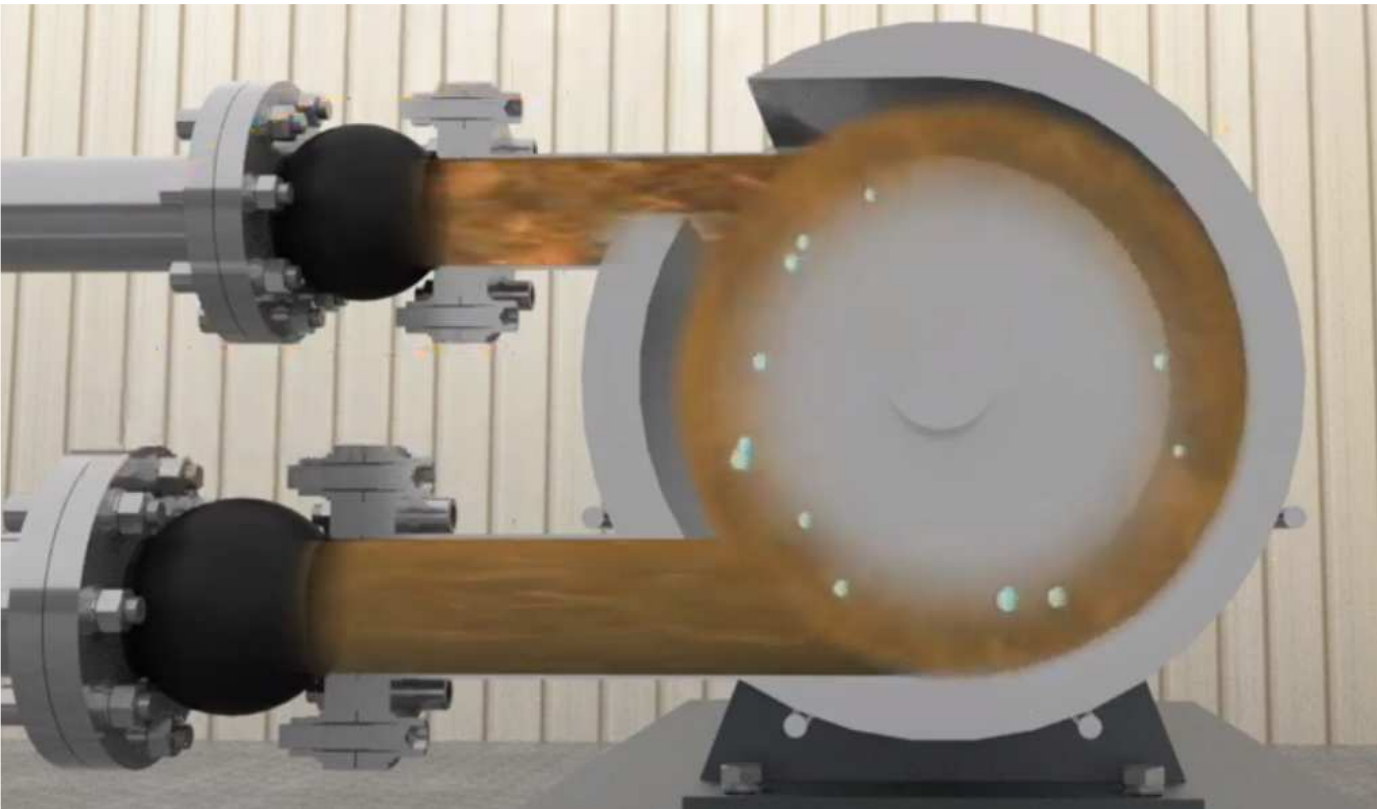


## ROTOR-STATOR HYDRODYNAMIC CAVITATION





## ROTOR-STATOR UNIT FOR HYDRODYNAMIC CAVITATION

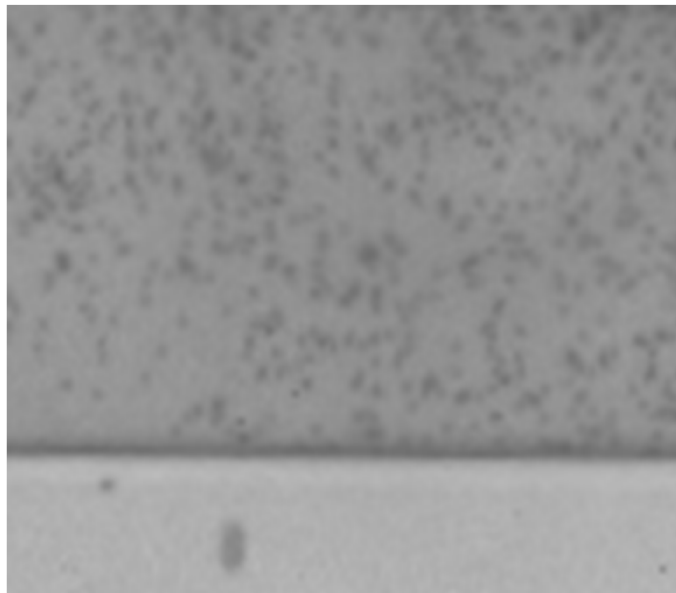


# ROTOR-STATOR UNIT FOR HYDRODYNAMIC CAVITATION





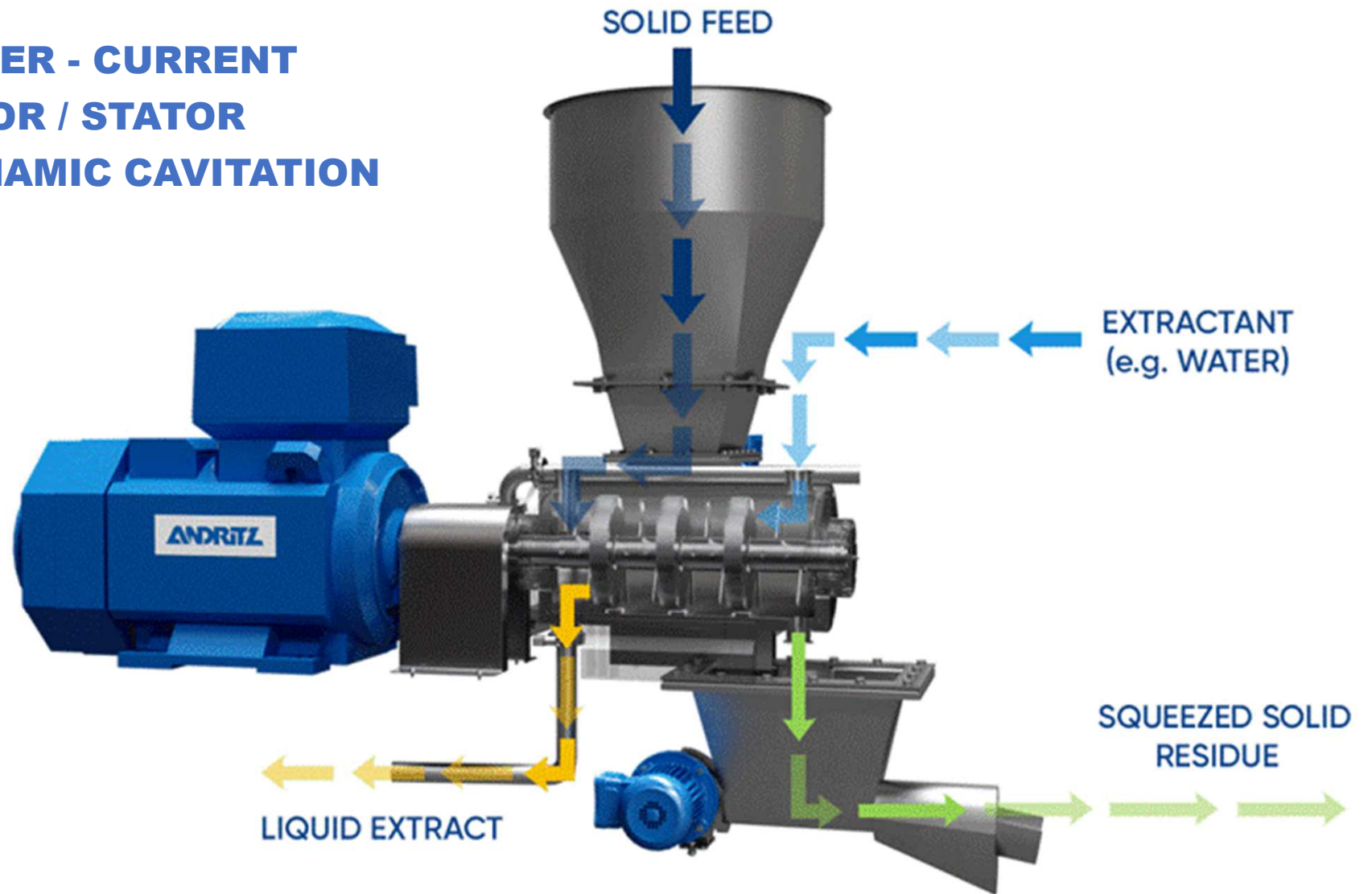
# HYDRODYNAMIC CAVITATION + ULTRASOUND



**FLOW MODE**  
**1 m<sup>3</sup>/h**



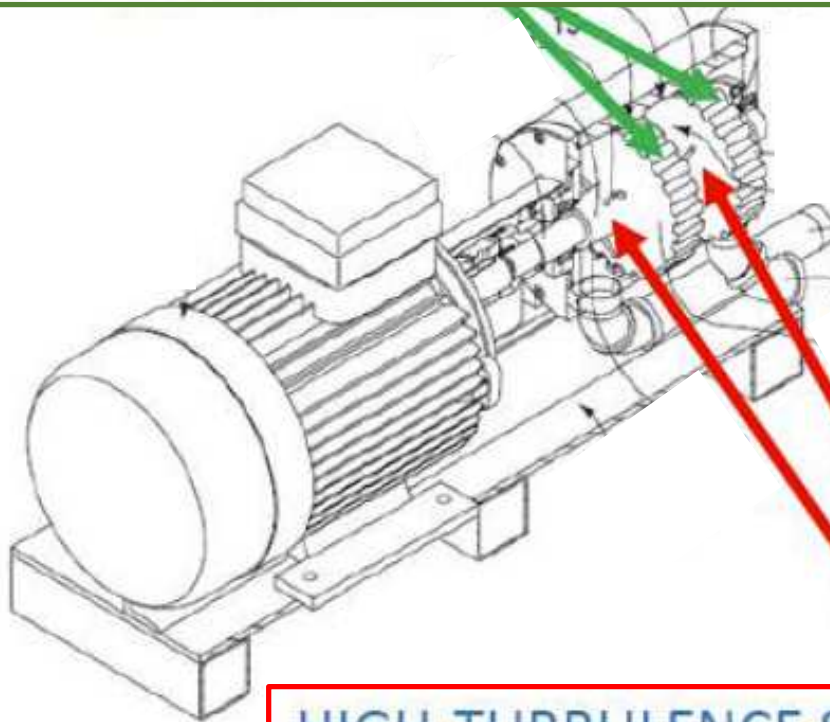
**COUNTER - CURRENT  
ROTOR / STATOR  
HYDRODYNAMIC CAVITATION**





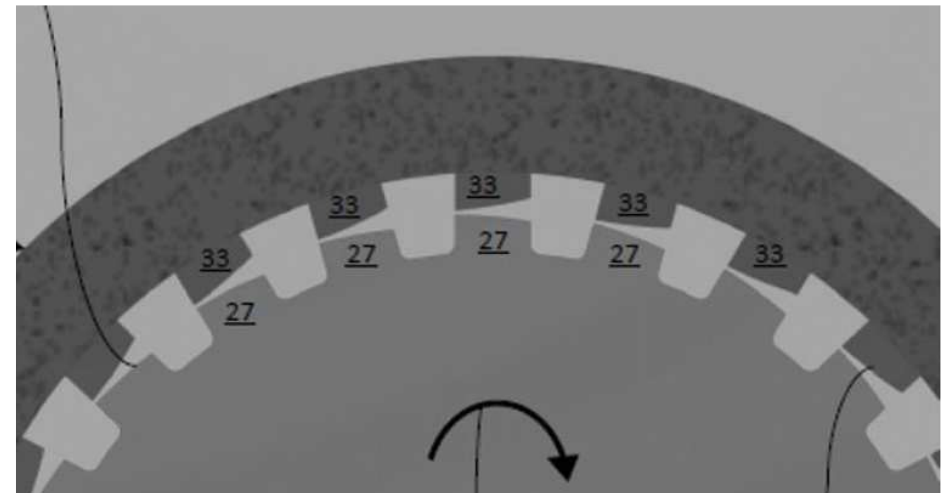
## COUNTER – CURRENT HYDRODYNAMIC CAVITATION

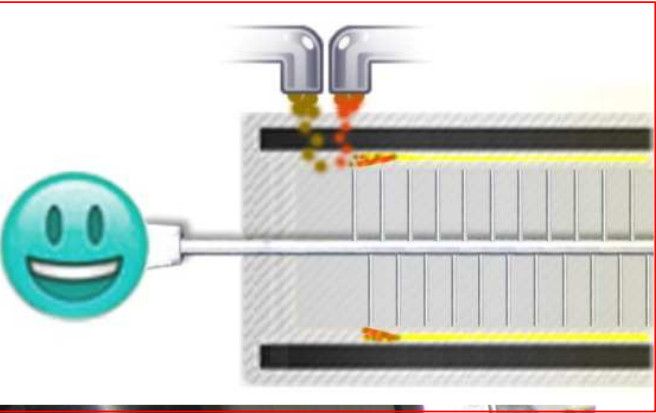
HIGH-SHEAR/HIGH CAVITATION STAGES



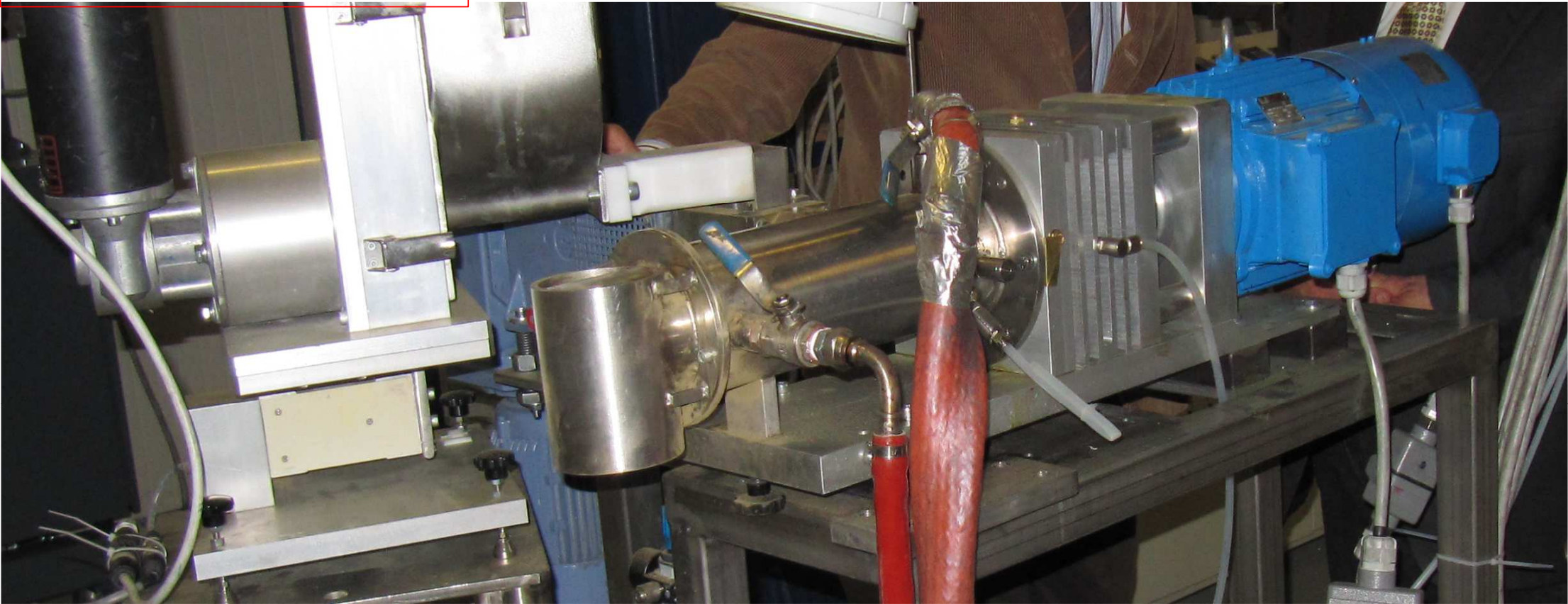
HIGH-TURBULENCE STAGES

**A multirotor-multistator configuration where one or more discs of suitable geometry alternate each other connected to a motor shaft which rotating inside a confined chamber, generate high friction with the fluid with which they come into contact and therefore creating cavitation.**



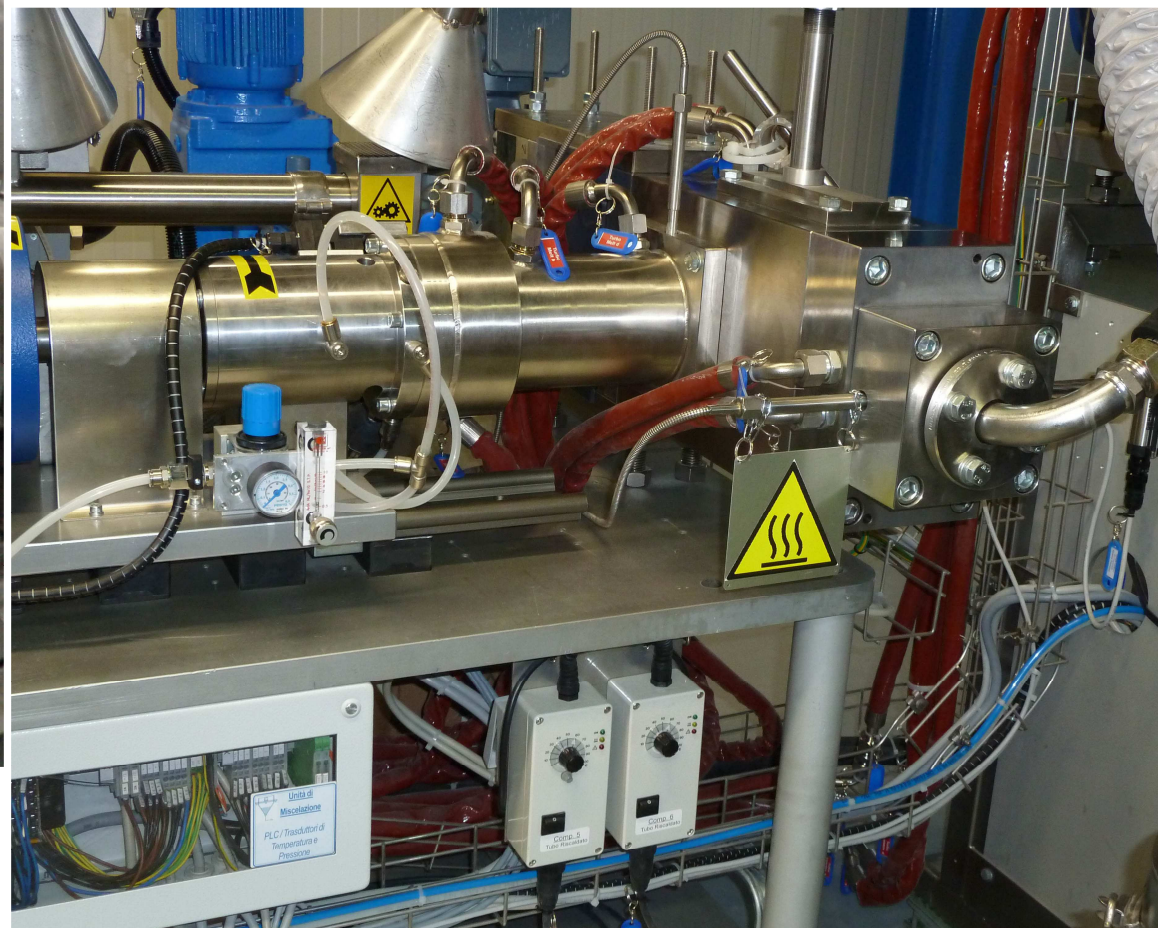
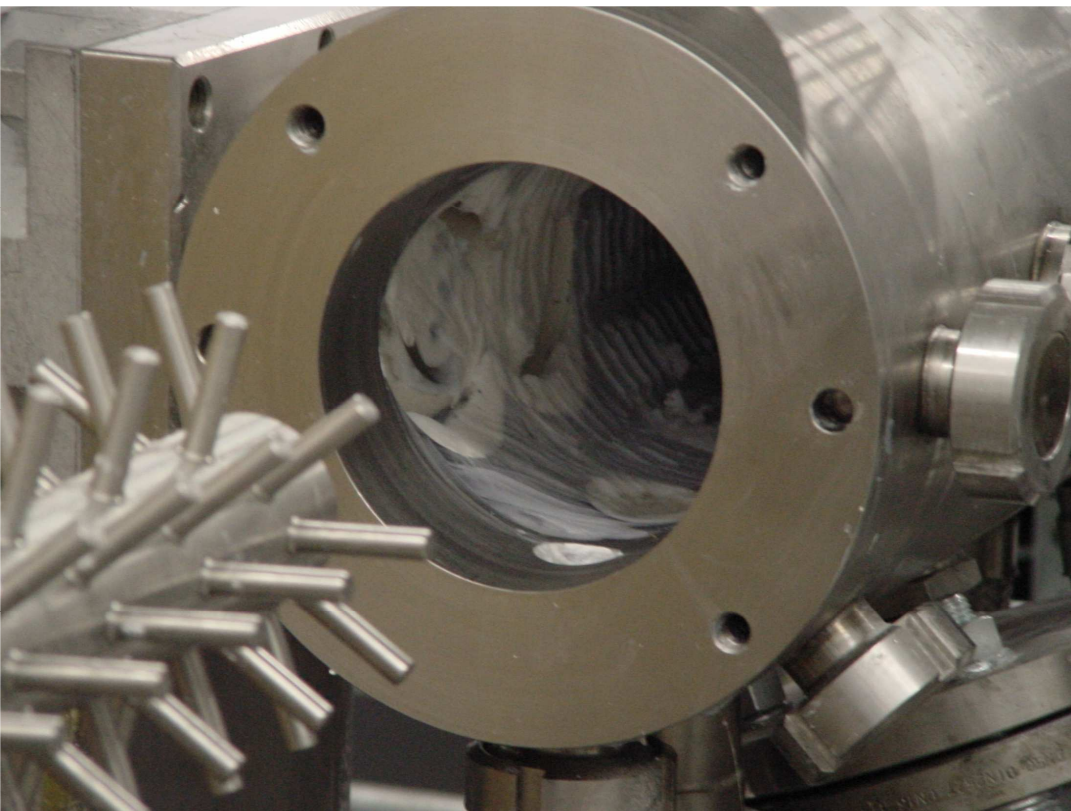


# FLOW-TURBINE TECHNOLOGY





# FLOW-TURBINE TECHNOLOGY





# Grape Pomace & Seeds

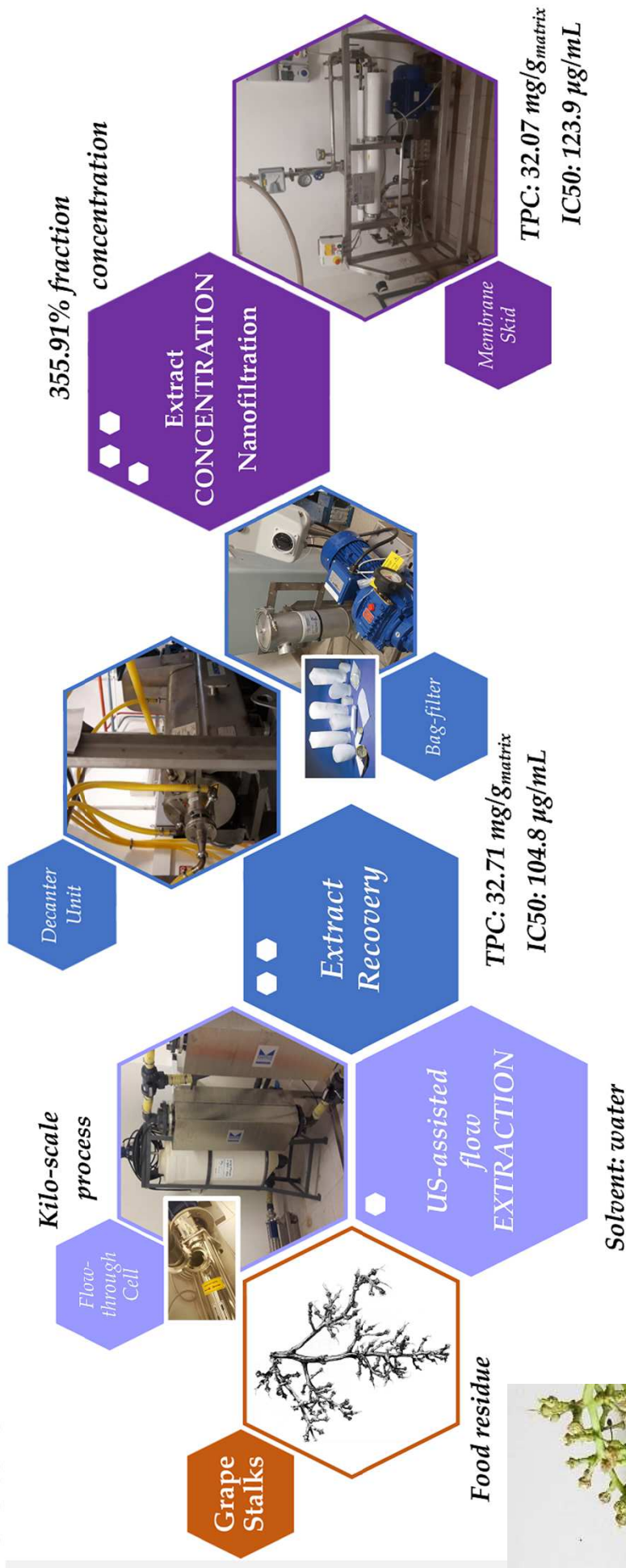




# Batch and Flow Ultrasound-Assisted Extraction of Grape Stalks: Process Intensification Design up to a Multi-Kilo Scale

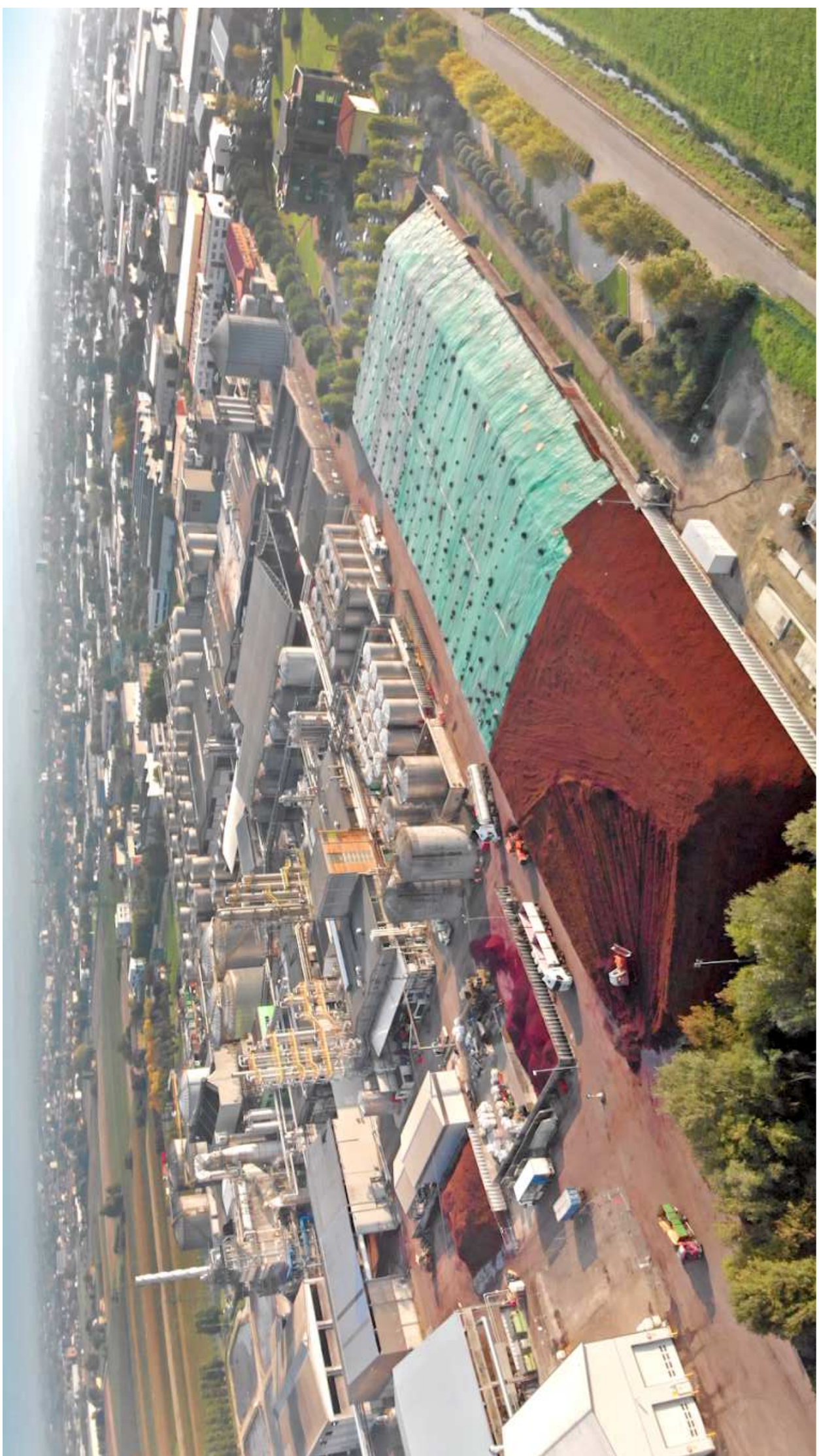


*antioxidants* 2020, 9, 730



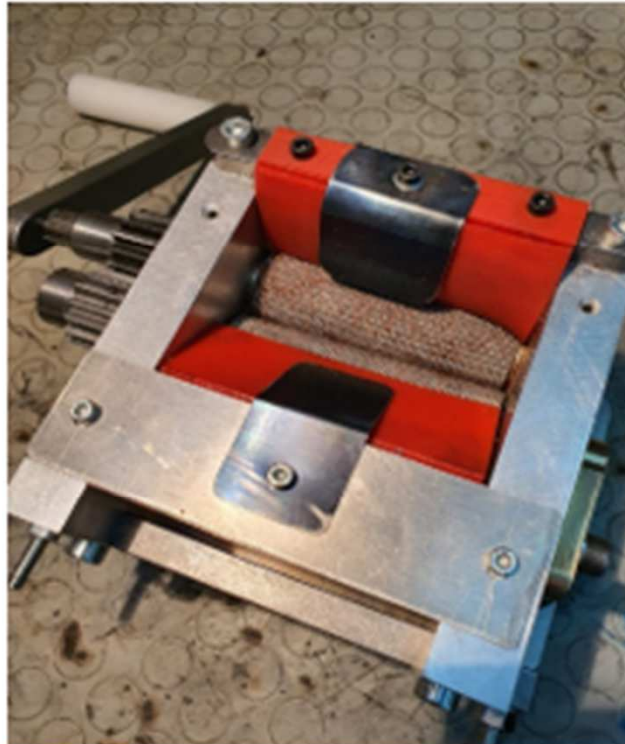








# Proteins extraction in crushed grape seeds



Milling process:

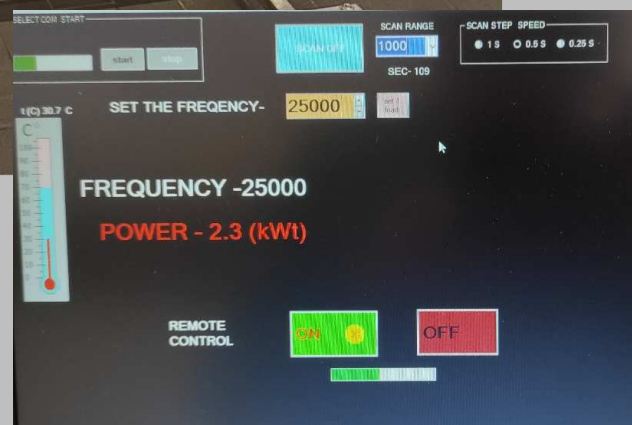
- Increases surface area
- Improves extraction yield
- Enhances mass transfer



From batch  
to flow-  
reactors



# Ultrasound flow-reactors





## ULTRASONIC FLOW REACTOR TWO MODULES - 3 KW - 25 kHz







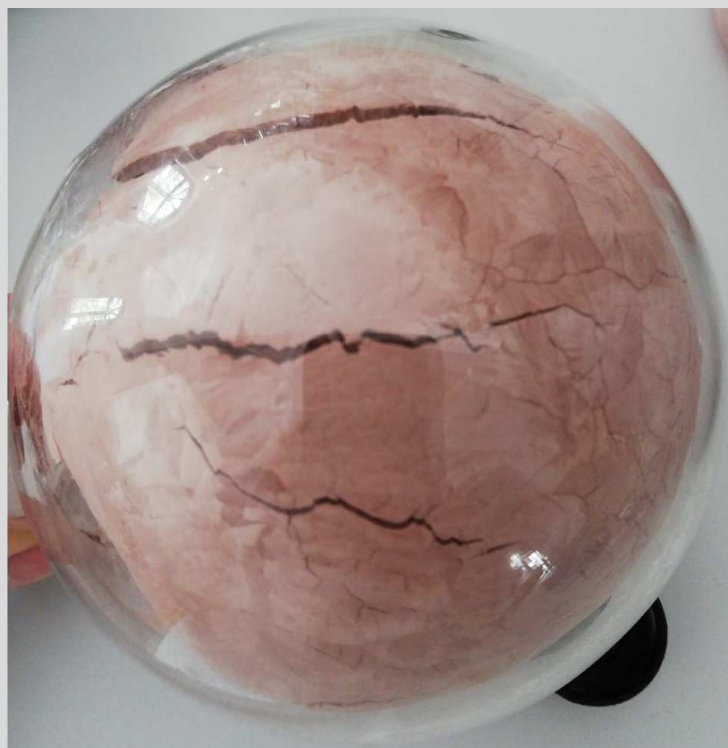


# Pilot-scale precipitation of proteins at different pH



|                                       | pH 5                                                                                 | pH 4                                                                                  | pH 3                                                                                  | pH 2                                                                                  |
|---------------------------------------|--------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
| Liquid fraction<br>(not precipitated) |  |  |  |  |
| Solid fraction<br>(precipitated)      |  |  |  |  |

# Raw Proteins Freeze-dried Extract



## Research Article

SCI  
where science  
meets business

Received: 18 October 2023

Revised: 6 February 2024

Accepted article published: 19 February 2024

Published online in Wiley Online Library:

(wileyonlinelibrary.com) DOI 10.1002/jsfa.13395

## Semi-industrial ultrasound-assisted extraction of grape-seed proteins

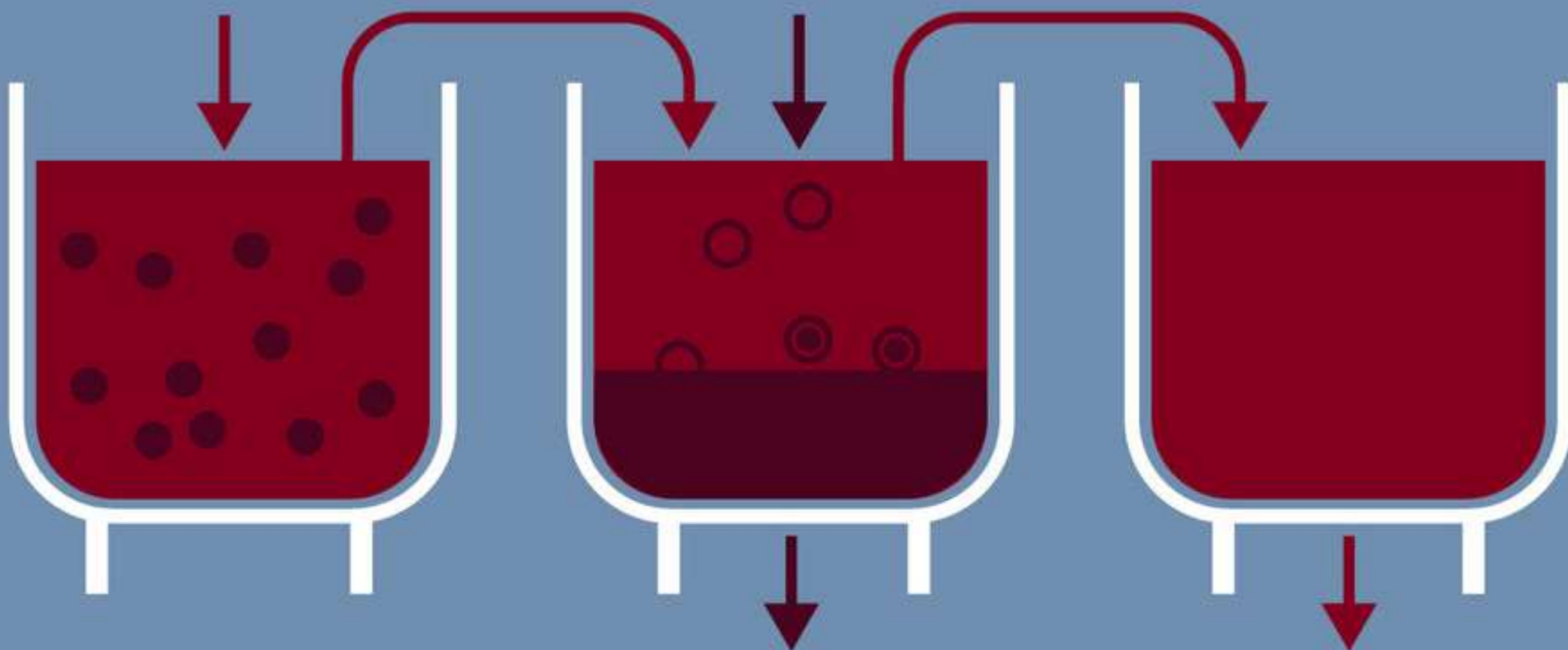
DOI 10.1002/jsfa.13395



## Raw proteins for wine clarification



RAW PROTEINS



## PURIFIED PROTEINS





# PULSED ELECTRIC FIELDS - PEF -



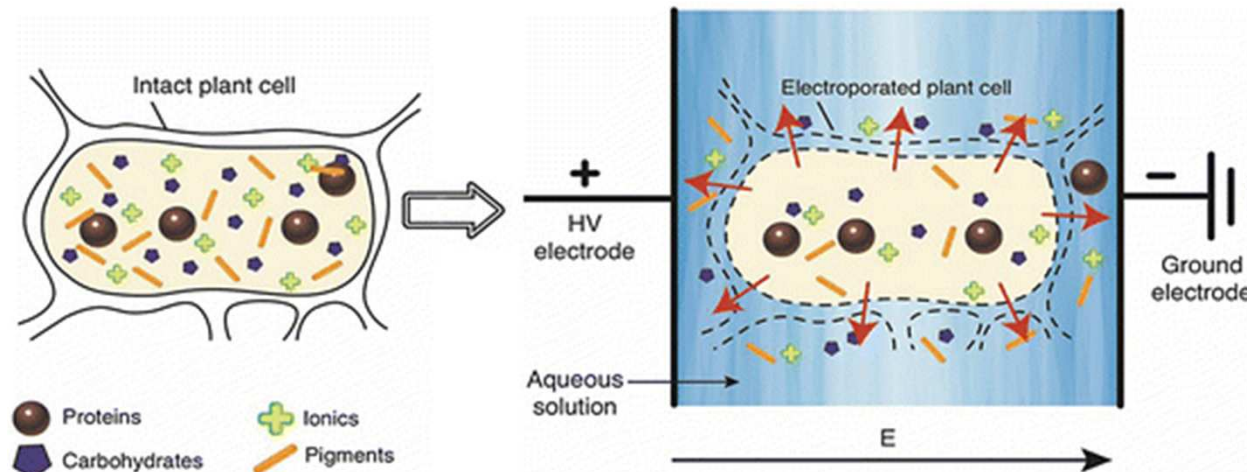
## PULSED ELECTRIC FIELDS ( PEF )



Antioxidants 2021, 10, 417

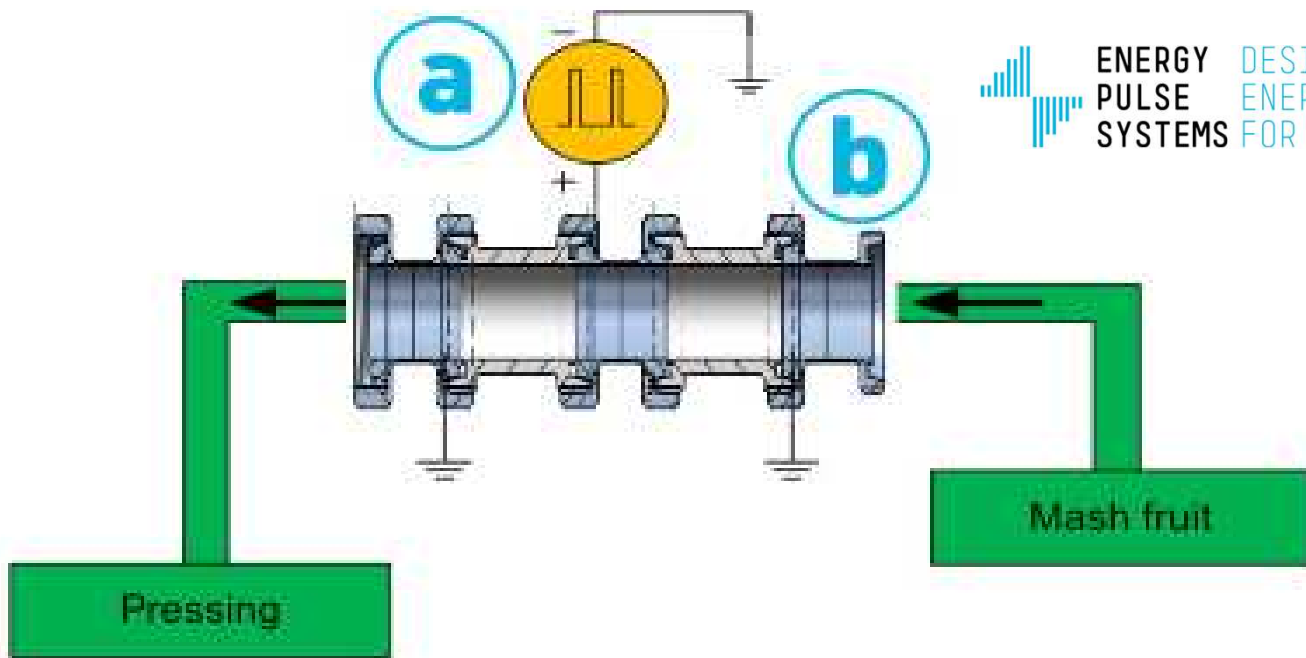
**Non-thermal technology for cell wall electroporation.**

The working principle of PEF is based on the application of pulses of high voltage (typically above 20 kV/cm up to 70 kV/cm) to liquid foods placed between two electrodes.





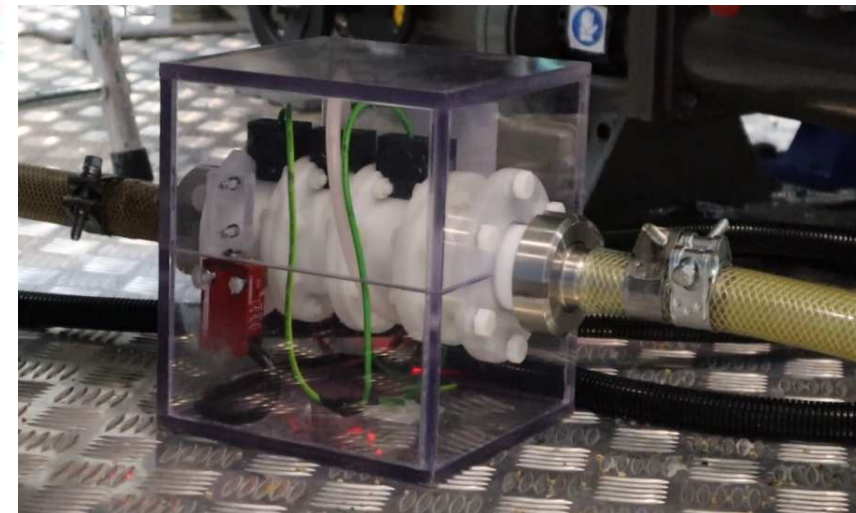
# PULSED ELECTRIC FIELDS ( PEF )



ENERGY PULSE SYSTEMS  
DESIGNING ENERGY FOR LIFE

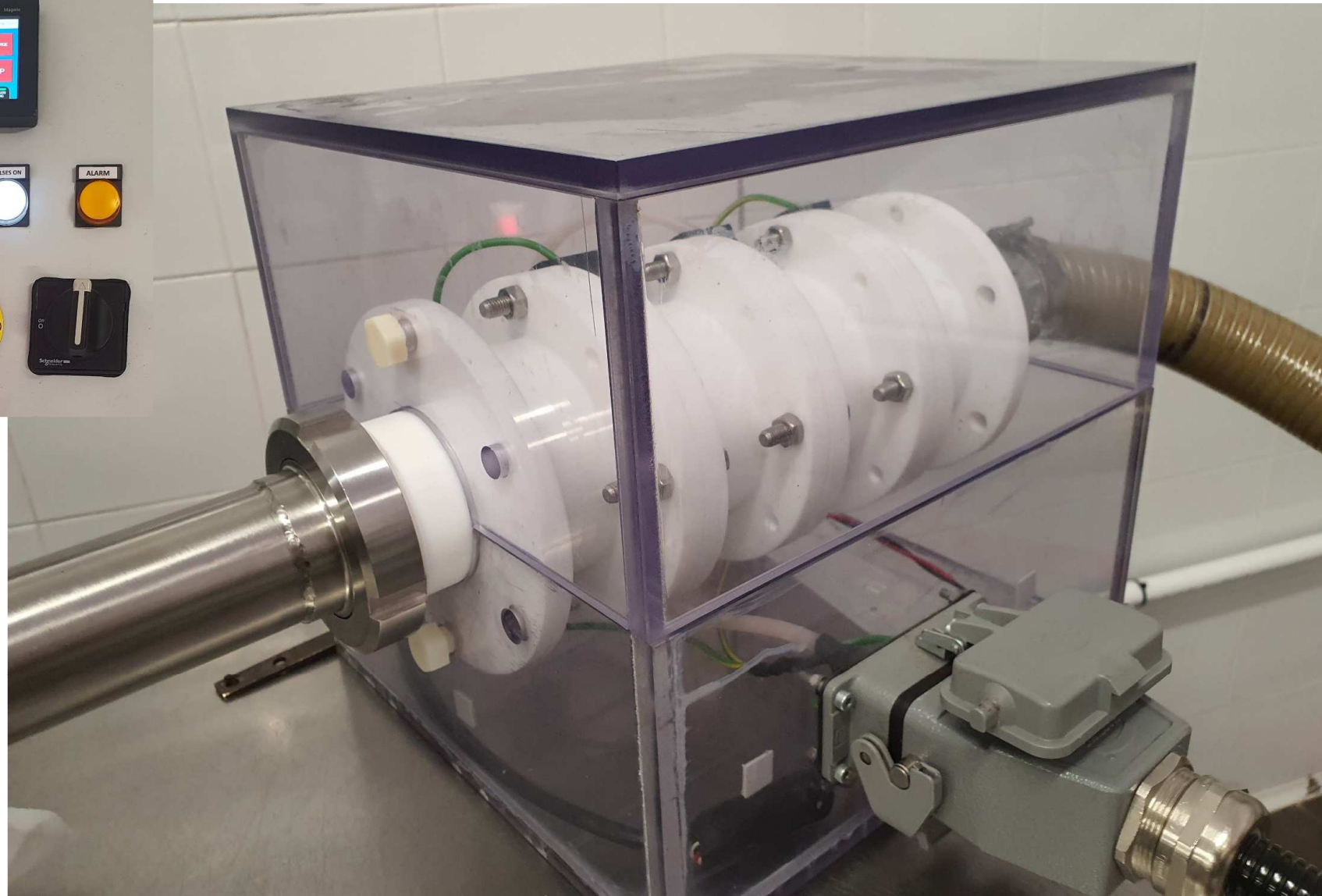
**a:** Generator.

**b:** Double co-field flow chamber (where the high-voltage pulses change into applied electric fields to the processed material).



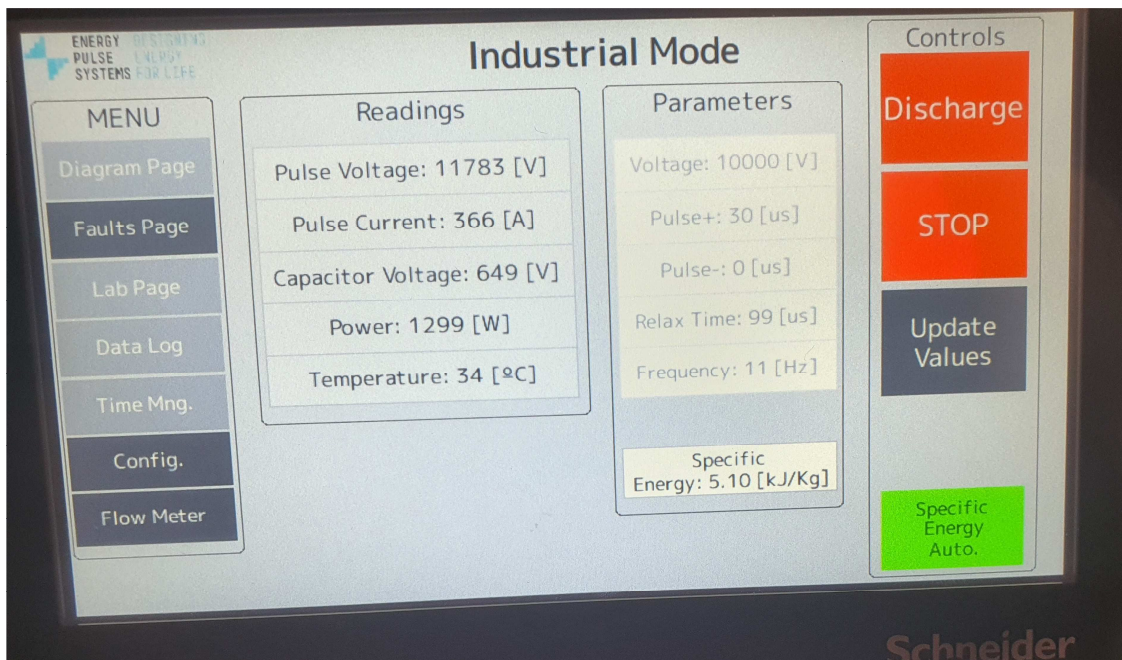


## INDUSTRIAL PEF



2.0 kV/cm  
5.1 kJ/kg  
1.5 kW  
30  $\mu$ sec; 17Hz







# SUBCRITICAL WATER EXTRACTION





## PRESSURE-RESISTANT MICROWAVE CAVITY “subcritical H<sub>2</sub>O”



HIGHER POWER DENSITY: **1.5 kW** / 1 L

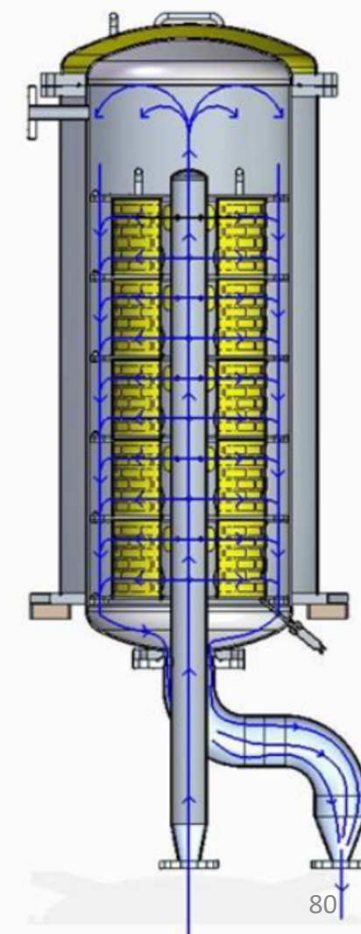
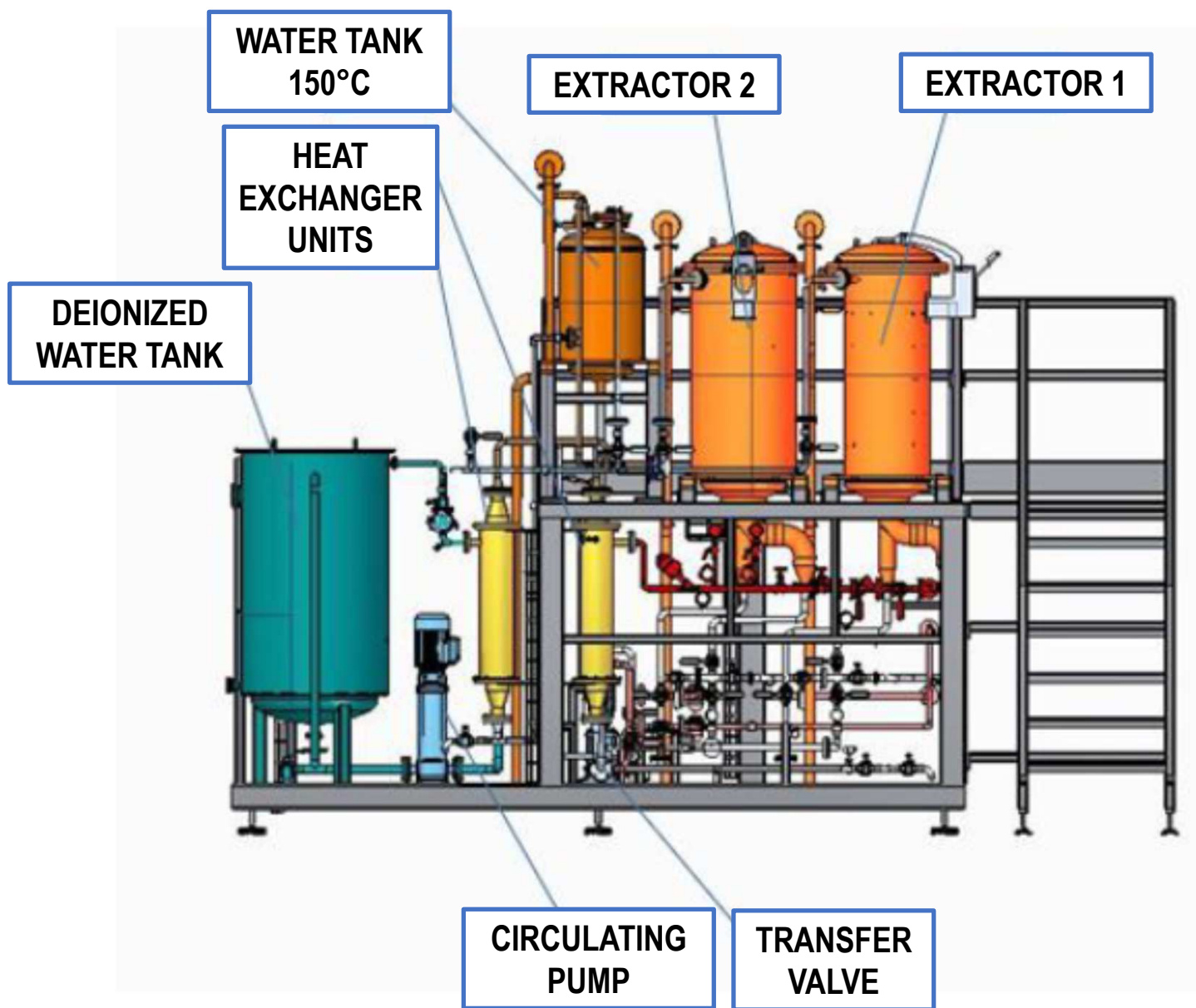
HIGH TEMPERATURE: **300 °C**

HIGH PRESSURE: **200 bar** (3 gas inlets)

FAST HEATING & COOLING (chiller)



# SUBCRITICAL WATER EXTRACTION

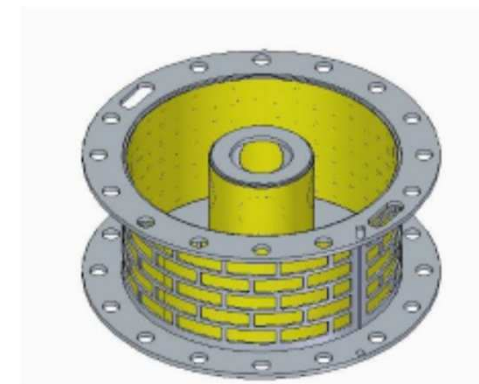
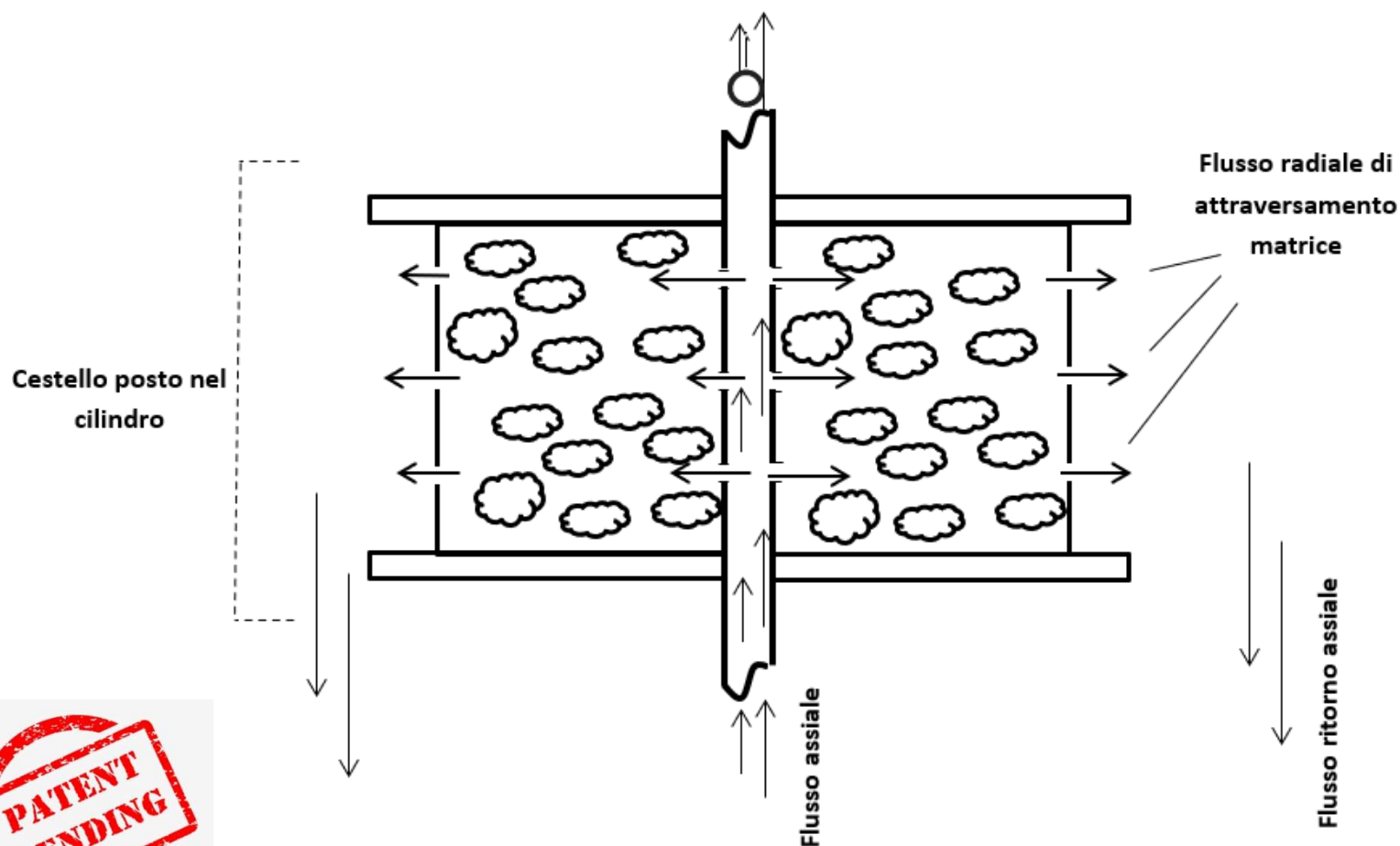




# EXTRACTION IN SUBCRITICAL WATER



**C<sup>2</sup>FUT**  
Food Upward  
Technologies

















EXTRACTION  
DOWNSTREAM  
PURIFICATION  
DRYING







## SOLID/LIQUID SEPARATION F2000 DECANTER







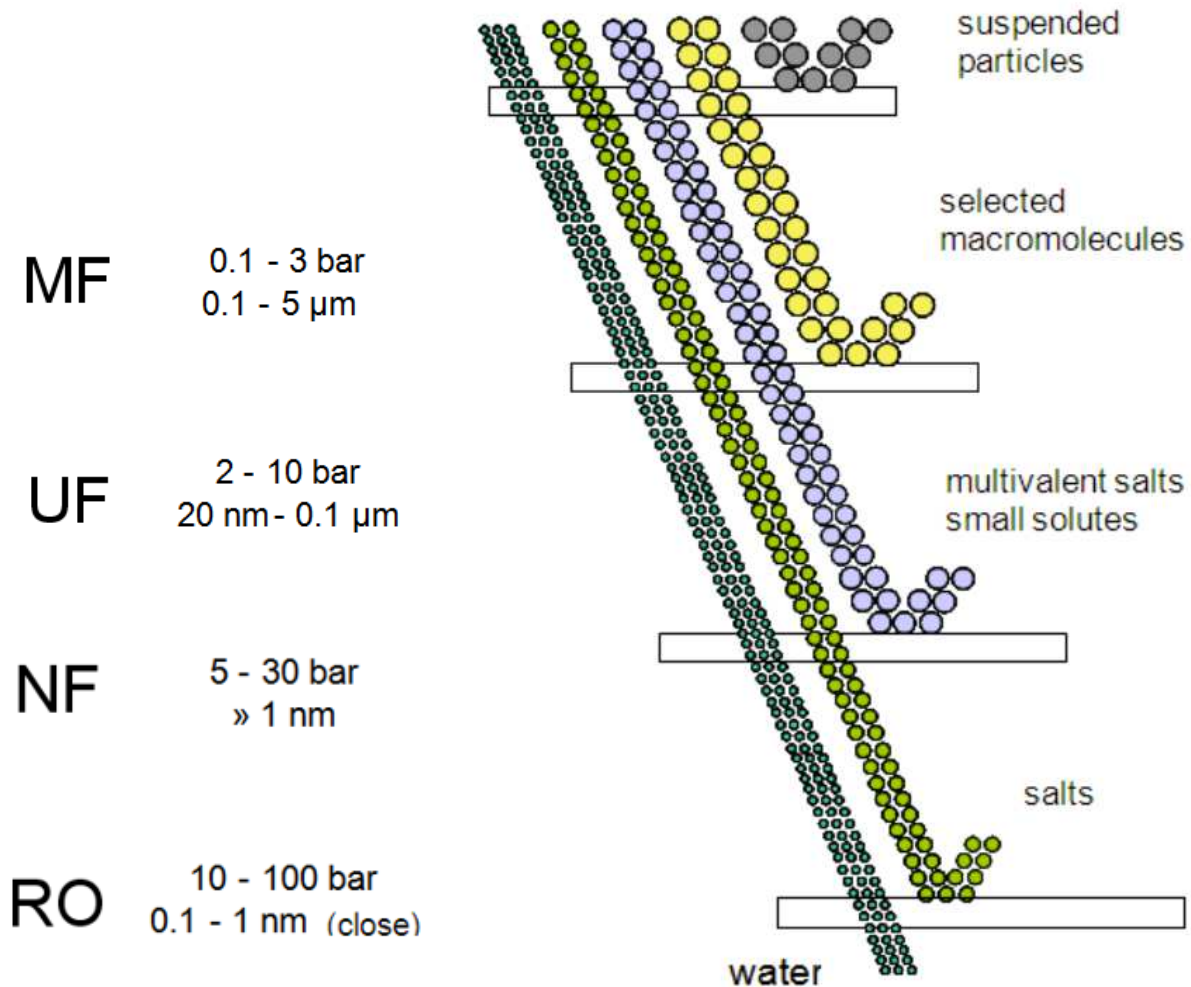


# BAG FILTER SKID RESIN SEPARATION





# Ultra- micro- and nano- filtration



## Ultra- micro- and nano- filtration





## SPRAY DRYERS



Scaling up new extraction technologies:  
high-value protein extracts from  
industrial residues



**POLITECNICO**  
MILANO 1863

DIPARTIMENTO DI CHIMICA,  
MATERIALI E INGEGNERIA CHIMICA  
GIULIO NATTA



Società Chimica Italiana