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Extraction Methods for Valorising Fibers in the Circular Economy

Valorization of Apple Pomace Through Ultrasound and Microwave-Assisted Extraction: Sustainable Technologies for High-Quality Pectin and Dietary Fiber Recovery

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COST Action CA24111 — ENFiber

European Cooperation in Science and Technology

Presenter: Liliana CECLU, PhD in Engineering Sciences

Aligning research with the ENFiber mission

COST Action CA24111

ENFiber

A pan-European network advancing extraction methods that unlock the value of fibers from agro-industrial side streams within the circular bioeconomy.

- **Sustainable extraction**
- **Side-stream valorization**
- **Circular bioeconomy**

Our contribution

Apple pomace as a model side stream

Industrially relevant

Apple juice production generates 25–30% pomace per fresh fruit weight.

Fiber-rich

≈ 20% pectin, plus polyphenols and bioactive compounds — yet largely underutilized.

Method-defining

Pectin quality is highly sensitive to extraction route — ideal benchmark for UAE vs MAE.

From by-product to bioresource

~ 20%

of apple pomace dry matter

is recoverable as pectin

Plus polyphenols, flavonoids, tannins, carotenoids and dietary fiber — yet most pomace is still discarded as waste.

Why this matters

Apple pomace is the dominant by-product of juice processing.

1 **Environmental burden**

High moisture, rapid fermentation, landfill emissions and odor problems near processors.

2 **Lost nutritional value**

Dietary fiber, pectin and bioactives are simply discarded with the cake.

3 **Economic inefficiency**

Disposal costs replace what could be a high-value functional ingredient.

Valorisation of the Apple Processing Chain

From the fresh fruit to high-value bioactive products recovered from pomace

Apple — Malus domestica

Energy 52 kcal · Water 86 g · per 100 g

▶ Vitamins

C — ascorbic acid · K — phylloquinone
B_1 thiamin · B_2 riboflavin · B_3 niacin
B_5 pantothenic · B_6 pyridoxine
E — α-tocopherol · A — β-carotene

vitamin C ≈ 4.6 mg / 100 g

▶ Minerals

K potassium 107 mg · P phosphorus 11 mg
Mg magnesium 5 mg · Ca calcium 6 mg
Cu, Mn, Fe, Zn — trace elements

support enzymatic and electrolyte balance

▶ Macronutrients & phytochemicals

Carbohydrates — 14 g (sugars 10 g)
Dietary fibre — 2.4 g
Proteins — 0.3 g · Lipids — 0.2 g

Polyphenols — quercetin, catechins, chlorogenic and phloridzin acid

natural antioxidant fraction

Apple-derived products

- **Fresh apples** — *whole-fruit consumption*
- **Apple butter / jam** — *concentrated spread*
- **Apple juice** — *clarified beverage*
- **Apple cider** — *fermented beverage*
- **Apple compote** — *stewed-fruit preserve*

APPLE POMACE

solid residue: peel · pulp · seeds · stems

≈ 25–30 % of the processed apple weight

Recovered bioactive products

Pectin

powder

Heteropolysaccharide used as a natural gelling, stabilising and thickening agent in food, pharmaceutical and cosmetic industries.

Bioactive compounds

Polyphenols (quercetin, catechin), flavonoids and triterpenoids — natural antioxidants for nutraceutical and pharmaceutical applications.

Dietary fibre

Soluble and insoluble fractions used as functional ingredients in bakery, dairy and meat products to enrich nutritional value.

Apple-pomace valorisation supports the circular bioeconomy and reduces agro-industrial waste.

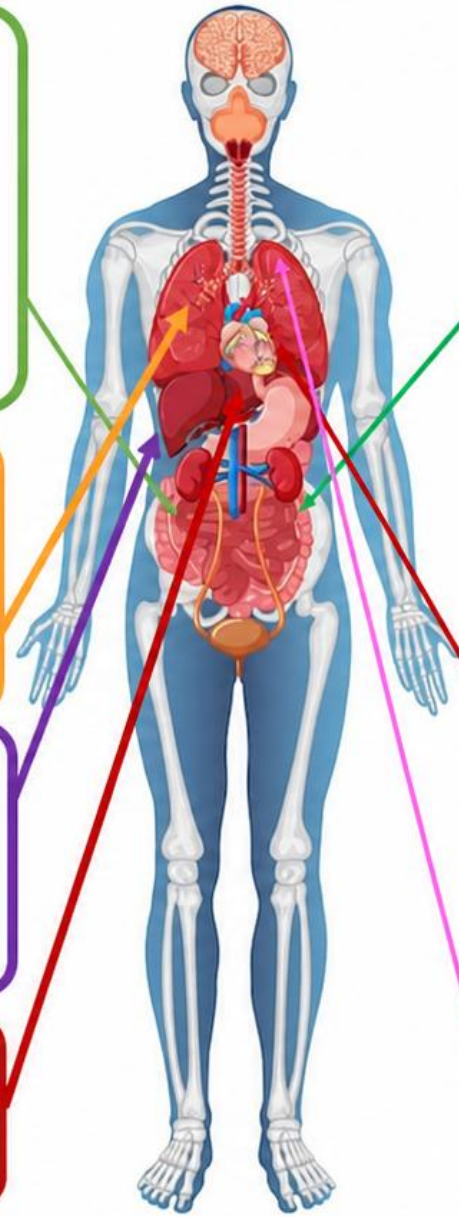
Pectin

Supports body weight management
Lowers cholesterol
Improves digestion
Prevents heavy metal toxicity

Reduces allergies
Positive effect on pulmonary mucosa-asthma

Strengthens the immune system
Antidiabetic effect
Inhibits lipase activity

Reduces the risk of cardiovascular disease



Contributes to satiety (appetite control)
Balanced gut microbiome
Prevents constipation
Eliminates harmful substances
Colon cancer
Obesity
Helps with diarrhea

Diabetes
Coronary artery disease
Prevents hypertension
Stable blood glucose level

Immune function strengthening

Apple pomace

Aim and objectives

AIM

To develop and optimize sustainable extraction technologies (UAE & MAE) for recovering high-quality pectin and dietary fibers from ‘Golden Delicious’ apple pomace, and to demonstrate their use as functional ingredients in food products.

Objective 1

Drying kinetics

Effect of hot-air temperature (60–80 °C) on drying behaviour, bioactive content and antioxidant capacity of apple pomace.

Objective 2

UAE optimization

Influence of ultrasound duration, solvent pH and solid-to-liquid ratio on pectin yield, structure and bioactivity.

Objective 3

MAE optimization

Effect of magnetron power, irradiation time, pH and solid-to-liquid ratio on pectin physicochemical and biological properties.

Objective 4

Food applications

Apply extracted pectin and pomace powder in vegetable bars and biscuits — characterize stability over storage.

Materials and methods overview

STEP 1

Raw material

Golden Delicious apple pomace

STEP 2

Convective drying

60 / 70 / 80 °C kinetic models

STEP 3

Pectin extraction

UAE & MAE optimization

STEP 4

Characterization

Physicochemical + bioactivity

STEP 5

Food application

Vegetable bars & biscuits

Pectin physicochemical analysis

Extraction yield · equivalent mass · methoxyl content · degree of esterification · anhydrogalacturonic acid · total polyphenols (Bouyahya) · DPPH antioxidant activity (Paulpriya).

Food product analysis

ISO sensory evaluation · moisture · titratable acidity · pH · water activity · CIELab color · texture profile · microbiological stability over storage.

EXTRACTION VARIABLES pH **1.0–2.5** · Solid-to-liquid ratio **1:10–1:20** · UAE time **15–30 min** · MAE time **5–10 min** · Power **450 / 650 W**

Two unconventional extraction routes

Both methods compared head-to-head with conventional acid hydrolysis as reference.

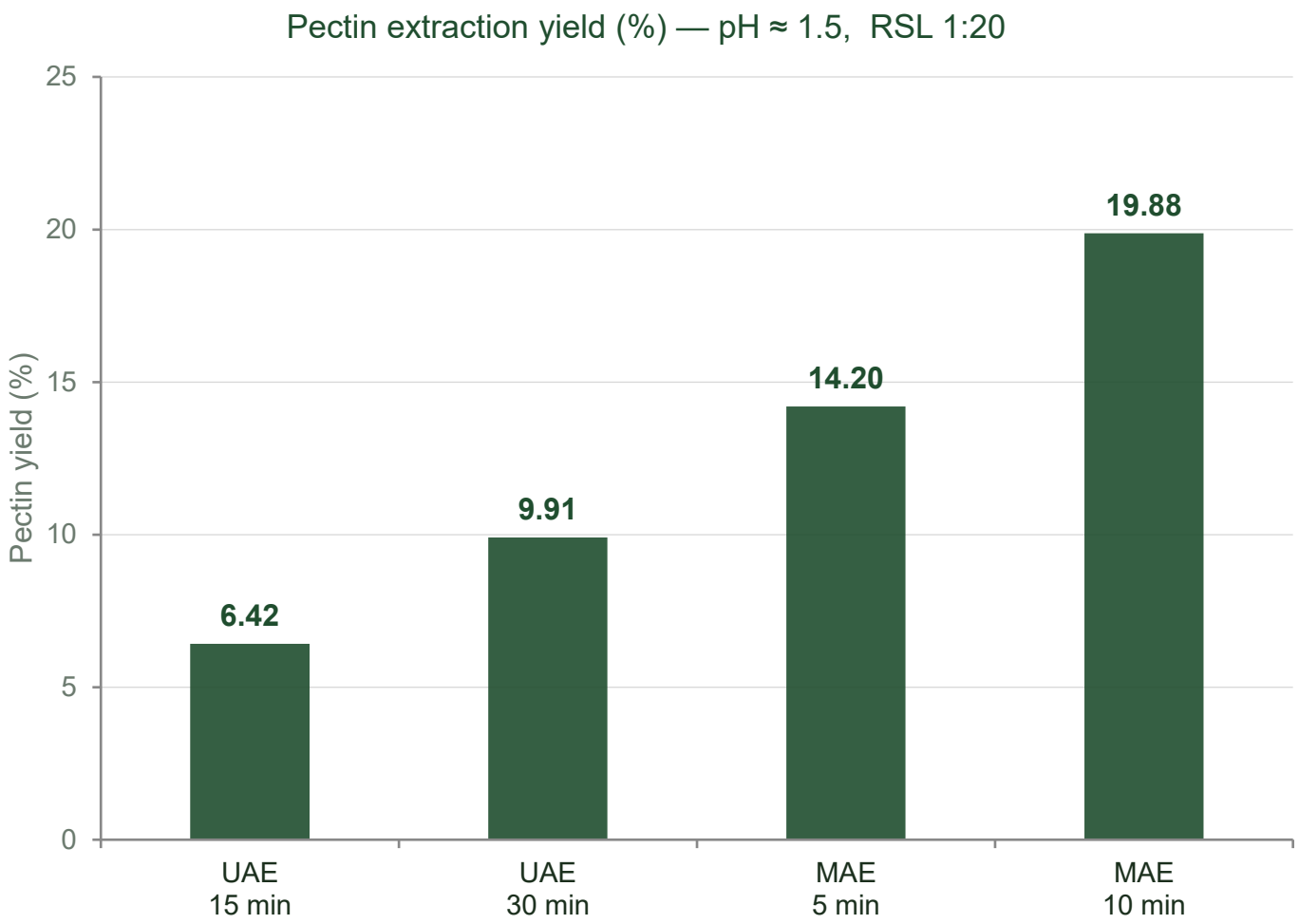
UAE
Ultrasound-Assisted Extraction

Frequency	37 kHz
Amplitude	100 %
Time tested	15 – 30 min
Solvent	Citric acid, pH 1.0–2.5
Mechanism	Acoustic cavitation — microjets disrupt cell walls

MAE
Microwave-Assisted Extraction

Frequency	2 450 MHz
Power	450 W & 650 W
Time tested	5 – 10 min
Solvent	Citric acid, pH 1.0–2.5
Mechanism	Dielectric heating — rapid intracellular pressure rise

MAE doubles the pectin recovered



19.88 %

MAE peak yield (10 min, 450 W)

9.91 %

UAE peak yield (30 min, 37 kHz)

× 2.01

MAE / UAE yield ratio under optimal conditions

A trade-off across structural attributes

Parameter	UAE (best)	MAE (best)	Winner
Extraction yield, %	9.91	**19.88**	MAE
Equivalent mass, g/mol	1 927	**2 261.7**	MAE
Methoxyl content, %	**6.81**	6.39	UAE
Degree of esterification, %	**73.78**	71.37	UAE
Anhydrogalacturonic acid, %	**78.71**	73.0	UAE
Total polyphenols, mg GAE/g d.m.	12.98	**13.05**	≈ tie
Antioxidant activity, µmol TE/g d.m.	**18.86**	16.39	UAE

Method choice = quality choice

MAE delivers

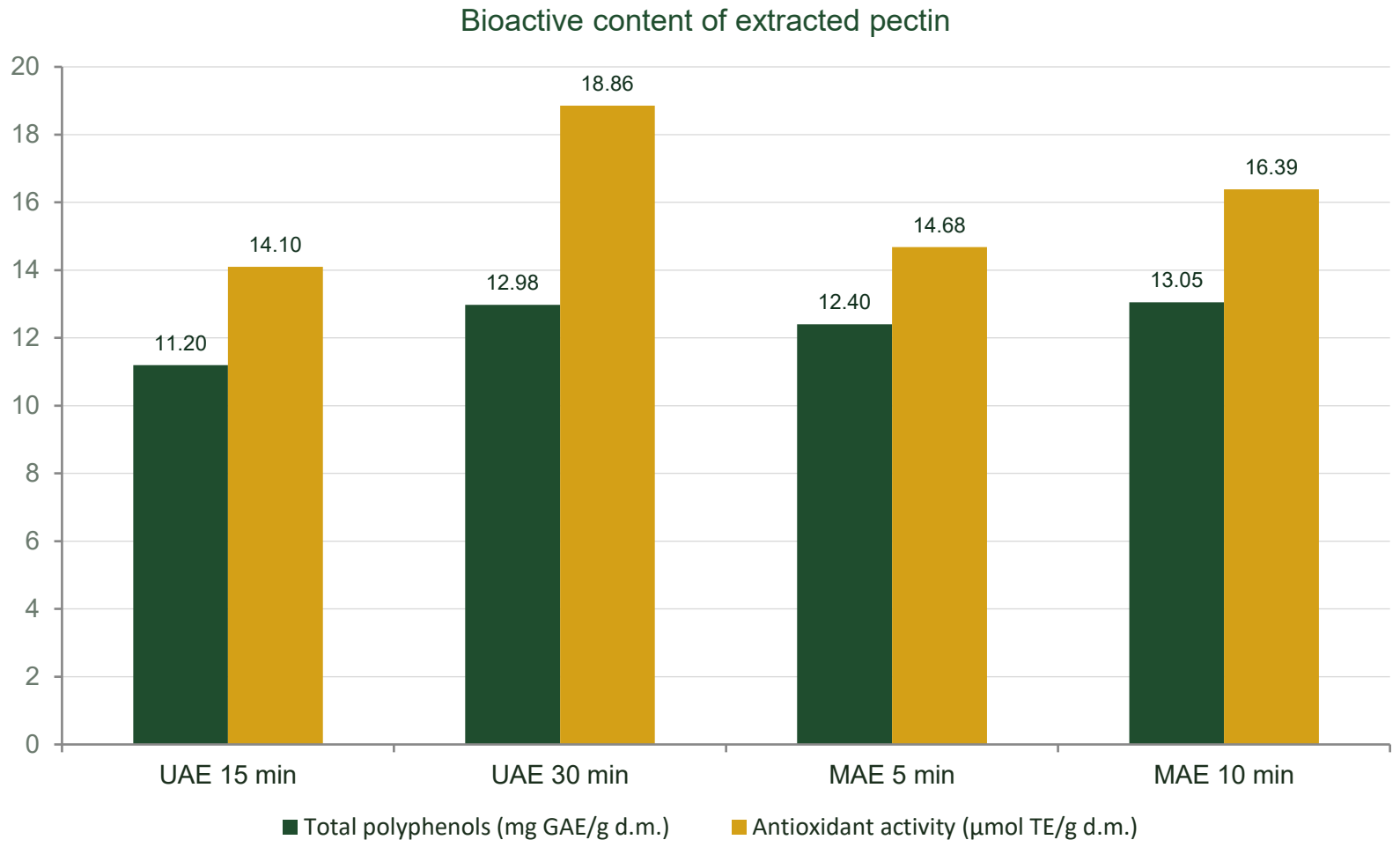
higher yield and longer pectin chains (equivalent mass).

UAE delivers

higher methoxyl, esterification and antioxidant activity — better for gelling.

Both yield high-methoxyl pectin (HMP, DE > 50%) suitable for jams, bars and confectionery.

Polyphenols and antioxidant capacity preserved by both methods



16.4 – 18.9

µmol Trolox eq. / g d.m.
(antioxidant activity range)

12.98 – 13.05

mg gallic acid eq. / g d.m.
(comparable polyphenol content)

Bioactive integrity preserved

Despite faster kinetics, MAE does not degrade phenolic compounds — a key advantage for functional ingredients.

Recommended parameters for each method

UAE

Ultrasound-Assisted Extraction

Frequency	**37 kHz, 100% amplitude**
Solvent	**Citric acid, pH ≈ 1.5**
Solid : liquid ratio	**1 : 20 (m/v)**
Duration	**30 min**

→ **Yield 9.91 % · DE 73.8 % · AOA 18.86 µmol TE/g**

MAE

Microwave-Assisted Extraction

Magnetron power	**450 W (2 450 MHz)**
Solvent	**Citric acid, pH ≈ 1.5 – 2.0**
Solid : liquid ratio	**1 : 20 (m/v)**
Duration	**10 min**

→ **Yield 19.88 % · Eq. mass 2 262 g/mol · AOA 16.39 µmol TE/g**

Vegetable bars — pectin as binder & coating

Formulation

- Dried apples
- Prunes
- Sour cherries
- Rosehip powder
- **MAE-extracted pectin (binder + coating)**

Role of pectin

Holds dry-fruit matrix together as a natural binder and forms a glossy protective coating that stabilizes moisture and limits microbial growth — patent MD 1653 Y / 2022.

Storage stability — 360 days

Vacuum-packed bars stored at ambient conditions

Moisture

30.0% → 23.6%

controlled, no drying out

pH

3.61 → 3.95

stable acidity

Antioxidant activity

24.85 → 20.14

µmol TE/100 g (×0.81)

Microbiology

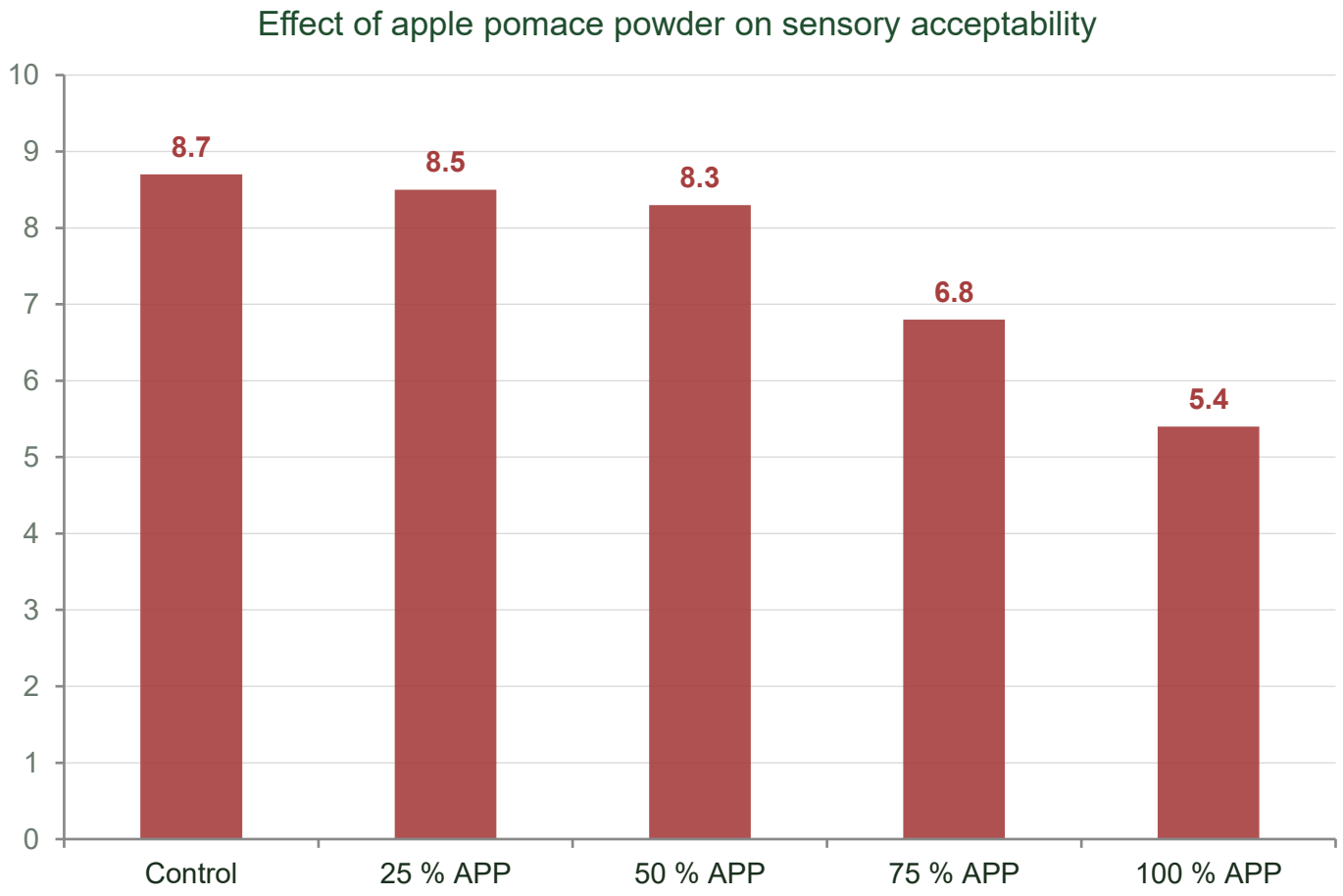
Within limits

barrier effect of pectin coating

No significant sensory deterioration over 12 months

Biscuits with apple pomace powder

Sugar replaced by dried apple pomace powder at 25, 50, 75 and 100 % substitution levels.



Optimal range

25–50 % sugar substitution: no significant sensory difference vs. control.

Nutritional gain

Higher dietary fiber, lower caloric density.

Color shift

CIELab L* drops ×1.3, a* rises (warmer brown hue) — appealing rustic look.

Microbiological

Stable for 30 days; moisture and alkalinity well within limits.

RESEARCH MATERIALS

Vegetable bars
Pectin Binding and coating agent

Biscuits with the addition of apple pomace powder to replace sugar (25%; 50%; 75% and 100%)

From orchard to functional food

Apple harvest

Orchard input

Juice processing

Pomace generated

UAE / MAE

Pectin & fiber recovered

Functional foods

Bars · biscuits · yogurt

Spent matter

Compost · animal feed

Circular bioeconomy outcome

An agro-industrial waste stream is reframed as a feedstock for high-value functional ingredients, extending shelf-life of foods, reducing solvent and energy use in extraction, and aligning with EU Farm-to-Fork and Green Deal priorities.

Key conclusions

MAE is the yield winner.

Up to 19.88% pectin recovery — twice the UAE peak — at only 10 min and 450 W.

UAE is the structure winner.

Higher methoxyl, esterification and antioxidant capacity — superior gelling pectin.

Both deliver high-methoxyl pectin (DE > 50 %)

Suitable for a broad range of food matrices, with comparable phenolic content.

Real, validated food applications.

Vegetable bars stable for 360 days; biscuits with 25–50% sugar substitution stable for 30 days, with no sensory penalty.

Tangible sustainability gains.

Reduced solvent consumption, energy use and processing time vs. conventional acid hydrolysis.

Practical recommendations for industry

EXTRACTION

How to extract

- UAE: 37 kHz · pH 1.5 · 1:20 · 30 min
- MAE: 450 W · pH 1.5–2.0 · 1:20 · 10 min
- Citric acid as green solvent
- MAE preferred when yield matters
- UAE preferred for premium gelling pectin

FORMULATION

Where to apply

- Pectin → vegetable / fruit bars
- · binder + protective coating
- Apple pomace powder → biscuits
- · 25–50 % sugar substitution
- Pomace powder → yogurt as stabilizer (0.6–0.8 %)

VALUE & IP

Demonstrated value

- Patents MD 1653 Y, MD 1661 Y
- Industrial implementation act issued
- 12-month shelf-life validated
- Compatible with vacuum packaging
- EU circular bioeconomy fit

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THANK YOU

Questions & discussion welcome

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