Engineered Biodegradable Coatings on Cellulosic and Biopolymeric Substrates for Active, High Barrier Packaging Solutions

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DEGLI STUDI DI SAL

Food packaging means:

- Containment and protection
- Food safety
- Easy transport and handling
- Presentation and information

- Food packaging constitutes the main volumetric fraction of municipal solid waste.
- 40% is made up of plastic

Sustainable packaging

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THE CHALLENGE

The **value chain of plastic packaging** needs a **deep transformation** in the perspective of **sustainability** and of the **Circular Economy principles,** in order to stop the environmental pollution caused by the huge quantities of waste produced by this sector all over the world.

CIRCULAR ECONOMY:
Plastic never becomes waste

The strategies

- Effectiveness of packaging systems
- Competitiveness
- Reduction of food waste

INNOVATION

- ☞ Nanotechnologies
- ☞ Active/Intelligent Packaging
- ☞ Replacement of multi-material with single-material solutions
- ☞ Active and Passive Coatings

SUSTAINABILITY

- ☞ **Raw materials from renewable sources**
- ☞ Implementing **mono-material packaging** solutions
- ☞ **Recycled raw materials**
- ☞ **Thickness/mass reduction**

Sustainable Packaging

Which are the CONSTRAINS ?

INDUSTRIAL FEASIBILITY

Use of conventional production technologies that are easily scalable at industrial level

SAFETY AND SUITABILITY FOR FOOD CONTACT

Use of additives and materials approved by the FDA and EFSA for food contact;
Verification of compliance with the requirements of the European regulation for materials intended for food contact (EU No 1935/2004 and subsequent).

Food packaging critical key points

- seal ability
- oxygen and vapor barrier properties
- antimicrobial and/or oxygen scavenging properties
- printability

BIODEGRADABLE POLYMERS AND CELLULOSIC SUBSTRATES

PROS

- Good mechanical, optical and rheological properties;
- Low toxicity of degradation products
- Rapid degradation rate after use
- Consumer attractive

CONS

- Scarce gas barrier properties
- Brittleness
- Limited processability
- Low thermal resistance;
- Scarce impact resistance

Some functional properties are not fully satisfactory, **limiting their applications to foods with a short shelf-life.**

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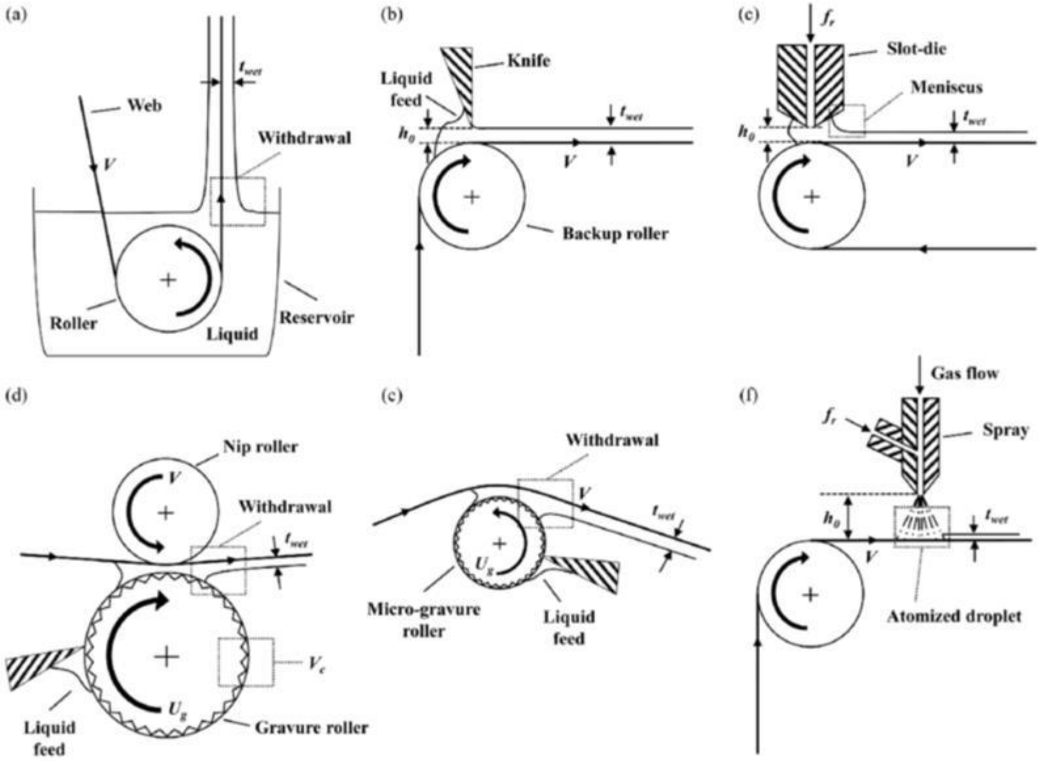
FEATURED APPROACHES

Nanocomposites, Blends,
Multilayers films,
Active phases,
Coatings

COATING TECHNOLOGY

COATING TECHNOLOGY

Process scalability
Process flexibility
Materials choices
Low cost
...



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Coating technology for realization of biodegradable multilayer films with enhanced functionalities for food packaging

Sustainability

- **100% biodegradable** materials;
- **Easy layer separation** in post-consumer phase

Applicability in food packaging field

- Materials **approved for food contact;**
- **Multiple functional properties** (*structural, barrier, sealability, water resistance*).

Industrial feasibility

- Films produced by film blowing and coating process, **conventional technologies easy scalable** at industrial level;

100% biodegradable multi-layers films

3 layers

POLYMERIC SUBSTRATE HIGH BARRIER

2° layer

1° layer

PLA/PBAT
BLOWN FILM

3 layers

CELLULOSIC SUBSTRATE HIGH BARRIER

2° layer

1° layer

KRAFT
PAPER

2 layers

POLYMERIC SUBSTRATE ACTIVE BARRIER

1° layer

PBS/PVOH
BLOWN FILM

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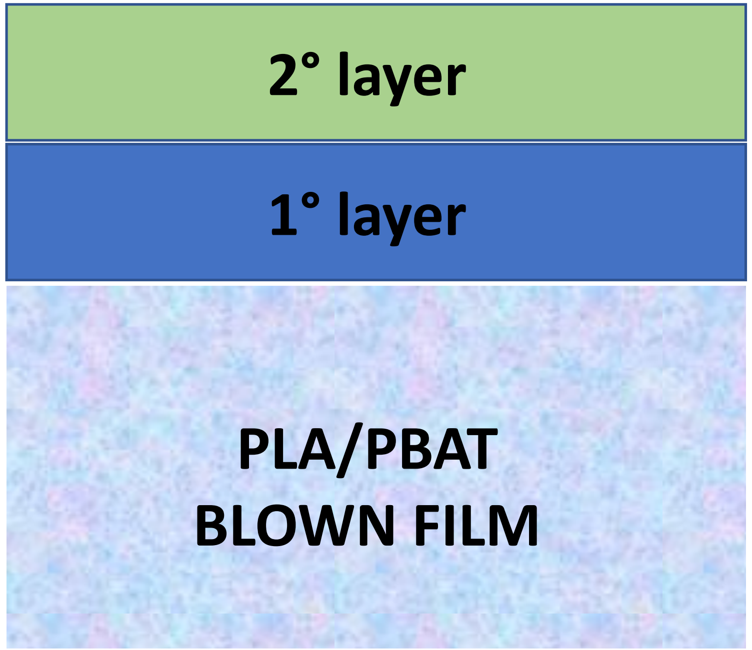
POLYMERIC SUBSTRATE
HIGH BARRIER

PLA-PBAT blown films COATED WITH PVOH and WAX



PLA-PBAT blown films COATED WITH PVOH and WAX

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2° layer COATING	*PLA + IDROPHOBIC WAX - H_2O Barrier Barrier/Sealable*
1° layer COATING	*M-PVOH coating - O_2 Barrier* Exceval AQ-4104. Water soluble: easy to be removed in post consumer phase, High barrier properties, Reduced moisture sensitivity due to chemical modification
PLA/PBAT BLOWN FILM	*blown film based on blends of PLA/PBAT*

PLA-PBAT blown films COATED WITH PVOH and WAX

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SUBSTRATE: Biofilm

Biodegradable blown film based on

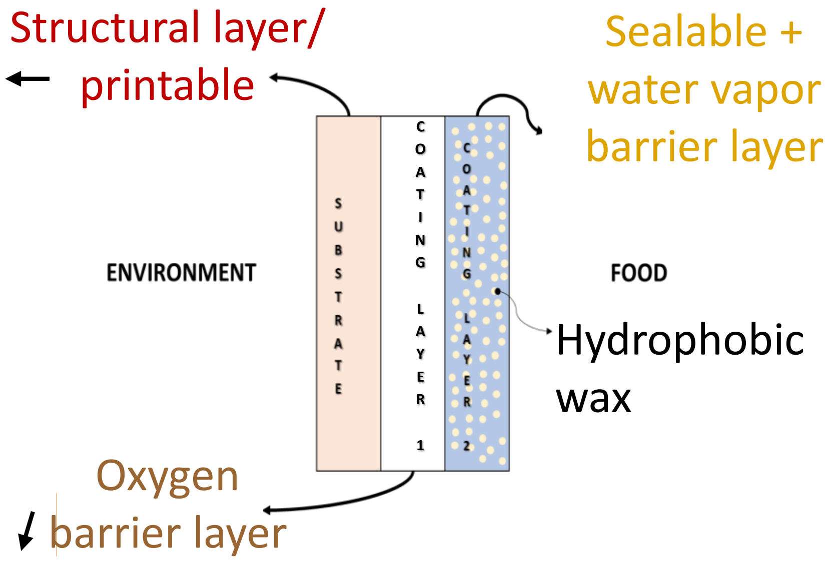
- **Polylactic acid (PLA 2003D)**
- **Poly(butyleneadipate-co-terephtalate) (PBAT)**

✓ Good ductility also at refrigeration temperatures; printability

COATING LAYER 1: m-PVOH Exceval AQ-4104

Fully hydrolyzed, water soluble, chlorine-free polyvinyl alcohol

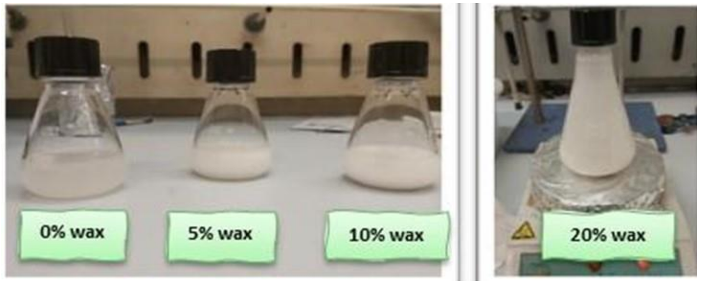
- ✓ **Barrier to gases and aroma**
- ✓ **Low sensitivity to moisture** (up to 60% RH, thanks to the chain modification*)



COATING LAYER 2: PLA+wax

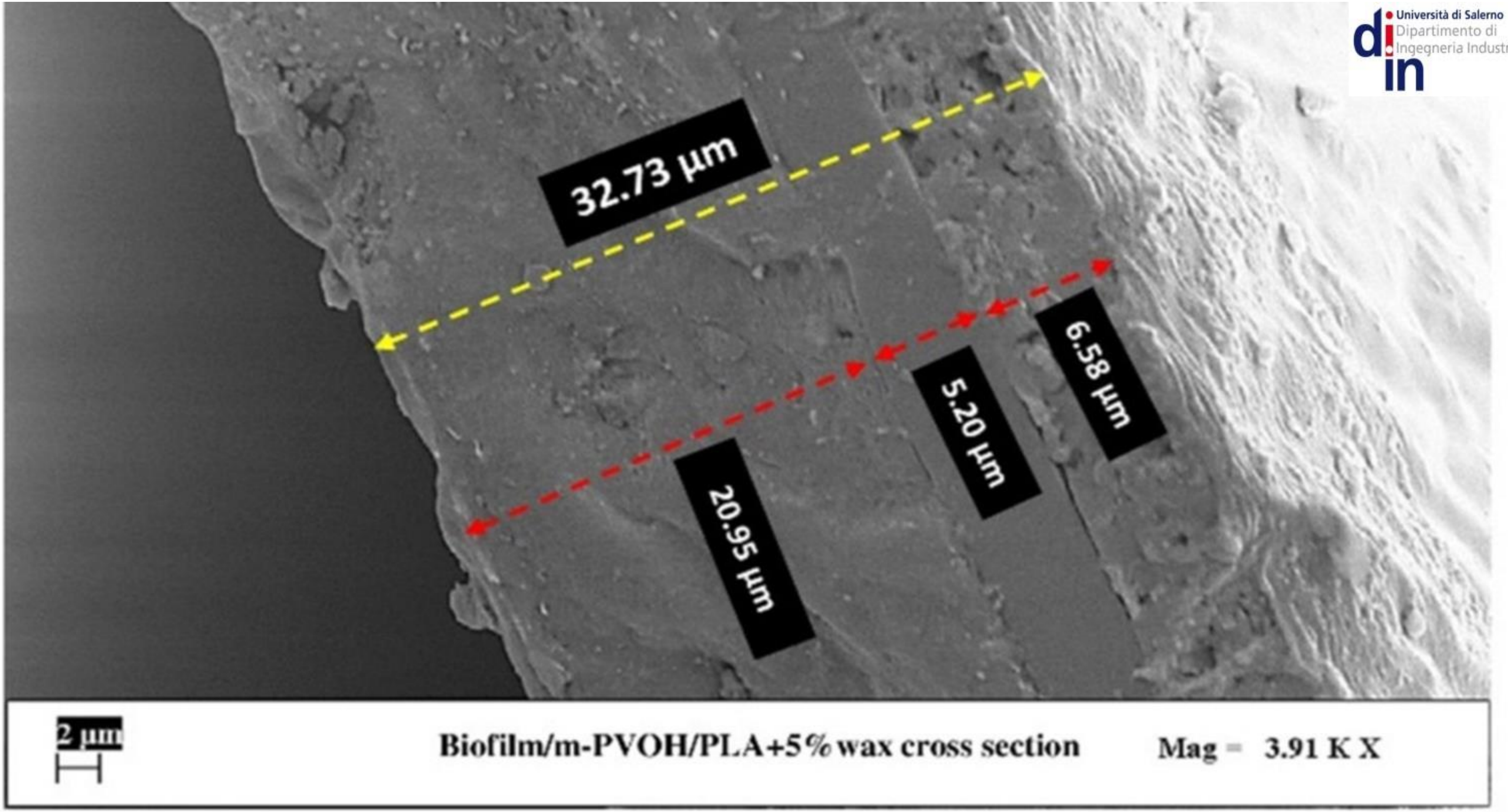
PLA4060 (Natureworks, USA) + **micronized EBS wax X2010M (DEUREX®, Germany)** (loaded at 5%, 10% and 20% w/w$_{PLA}$) **deriving from the valorization of sugar cane waste**

- ✓ **Sealability provided by PLA**
- ✓ **Moisture resistance provided by the wax**



DEUREX® Bio-based and micronized VEGETABLE Ethylene-Bis-Steramid wax (EBS)

**Kuraray Europe GmbH. Exceval™—Attractive Protection for Your Food. Available online: https://www.kuraray-poval.com/*



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PLA-PBAT blown films COATED WITH PVOH and WAX

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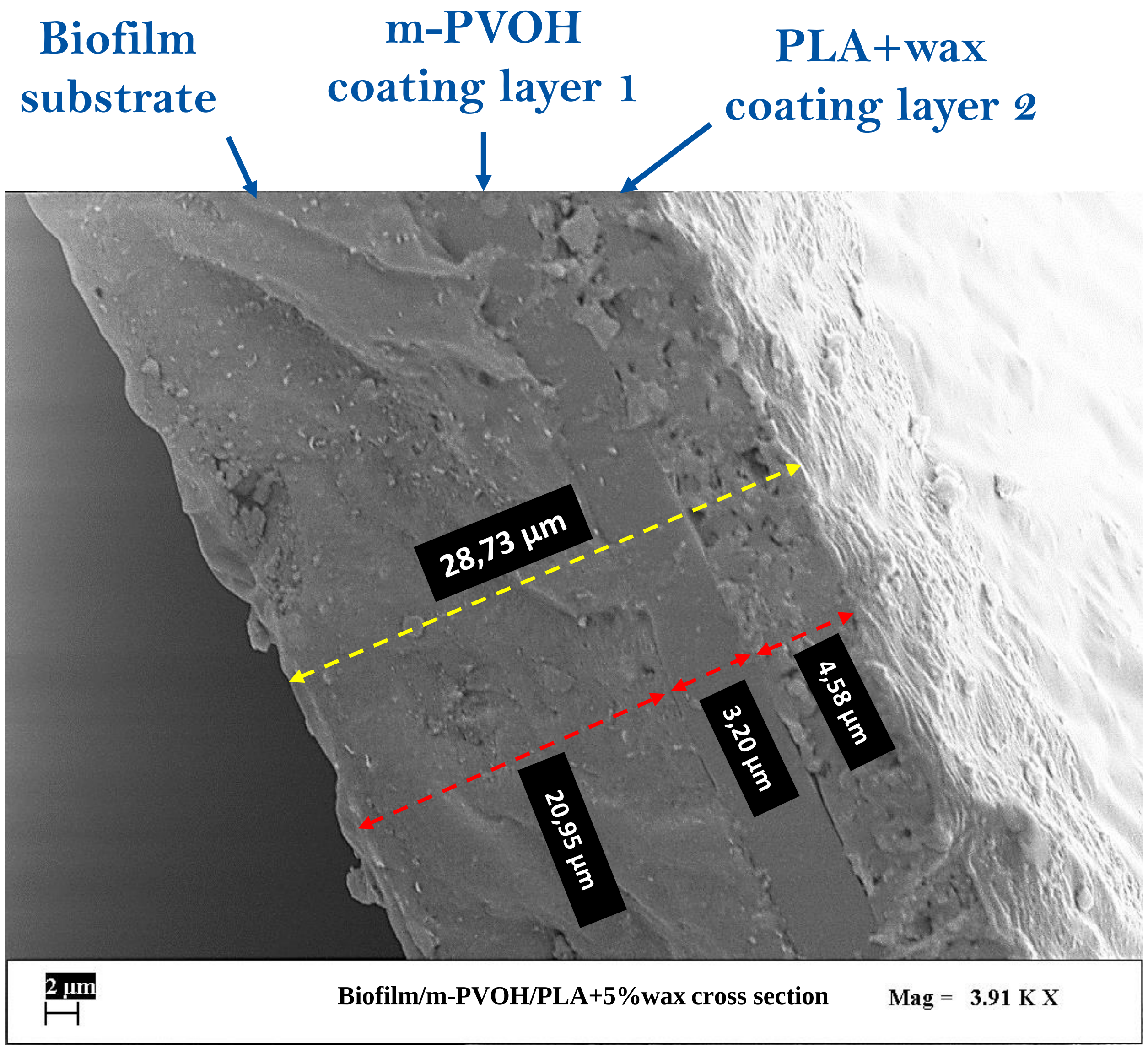

Films morphology and quality of interlayer adhesion

- **Good interlayer adhesion for both the m-PVOH and PLA coating layers**, with no boundary lines or voids in the whole cross-sectional area of the investigated films;
- **Good control** of the layers thickness during the coating process.
- **No delamination** occurred by increasing wax content

PLA-PBAT blown films COATED WITH PVOH and WAX

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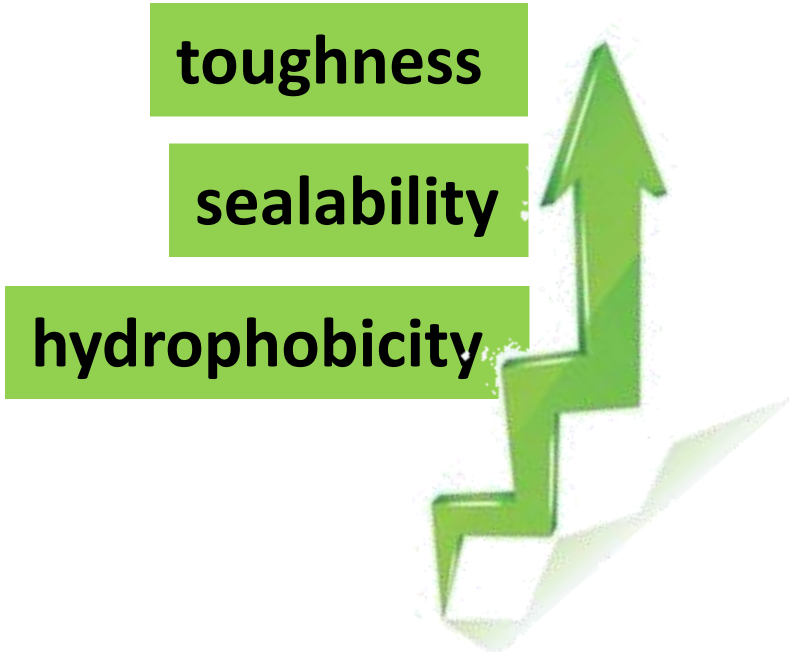
OXYGEN BARRIER PROPERTIES

23°C; 0% R.H. Sample films	Thickness, [mm]	P_{O_2} $\left[\frac{cm^3\,mm}{m^2\,d\,bar}\right]$
Biofilm	0.022	**48.4**
Biofilm/m-PVOH	0.028	**0.22**
Biofilm/m-PVOH/PLA+0%wax	0.034	**0.33**
Biofilm/m-PVOH/PLA+5%wax	0.038	**0.31**
Biofilm/m-PVOH/PLA+10%wax	0.038	**0.32**
Biofilm/m-PVOH/PLA+20%wax	0.039	**0.30**



The proper design/combination of supports and coatings allows to keep the toughness of PLA/PBAT system with the barrier properties of m-PVOH and with the seal ability and hydrophobicity provided by the PLA layer with natural wax.

PLA-PBAT blown films COATED WITH PVOH and WAX

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Multilayer films with wax are classified as <u>HIGH</u> oxygen barrier grade

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Biofilm/m-PVOH/PLA+20%wax	0.039	0.30

P_{O2} decrease of up to 2 o.o.m.

Classification of the biodegradable polymers depending on barrier perfomance (J. Wang et al.,2018)

Barrier grade	P_{O_2} $\left[\frac{cm^3\ mm}{m^2\ d\ bar}\right]$	Examples
High	<4	PGA, PVOH
Medium	4-40	PHAs, PPC, crystallized PLA, amorphous PLA
Low	40-400	PBS
Poor	>400	PBAT, PCL

Biofilm/m-PVOH/PLA+wax

Biofilm substrate

PLA-PBAT blown films COATED WITH PVOH and WAX

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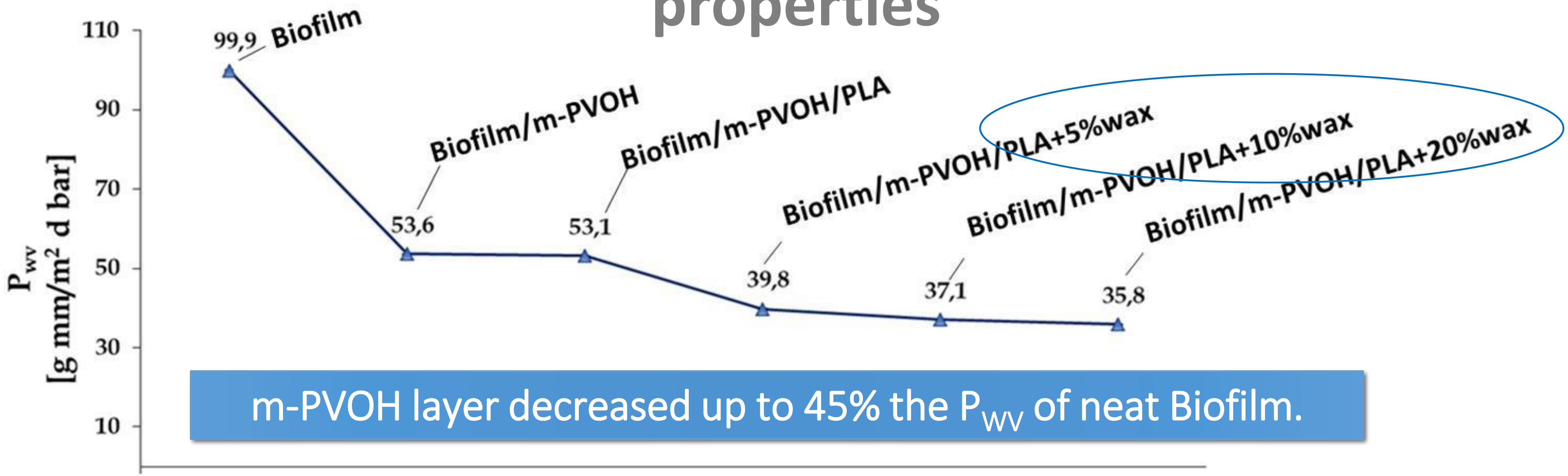
Water vapor barrier properties



Wax addition in PLA effectively hinders the vapor permeation into multilayer structure further improving water vapor barrier and protecting m-PVOH against moisture.

PLA-PBAT blown films COATED WITH PVOH and WAX

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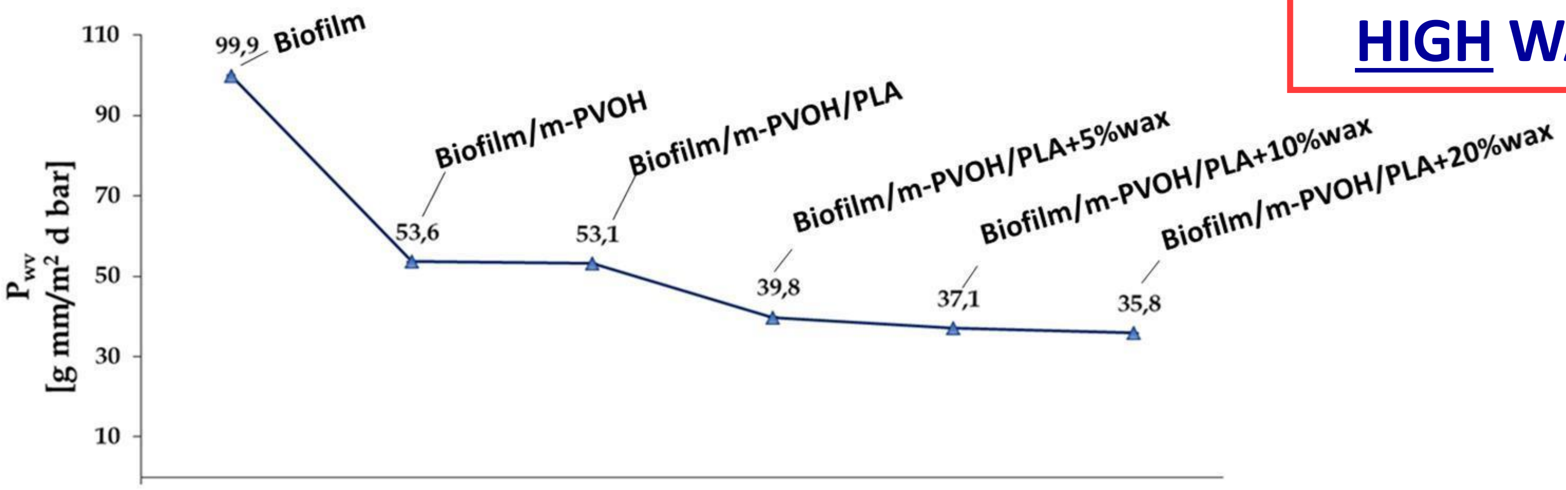
Classification of the biodegradable polymers depending on barrier perfomance (J. Wang et al., 2018)

Barrier grade $P_{WV}\left[\frac{g\,mm}{m^2\,d\,bar}\right]$		Examples
High	<40	PGA
Medium	40-100	PHAs,
Low	100-300	Crystallized PLA, PPC
Poor	>300	Amorphous PLA, PBS, PBAT, PCL, PVOH

Biofilm/m-PVOH/PLA+wax multilayer films

Biofilm substrate

Multilayer films with wax are classified as <u>HIGH</u> WATER VAPOR BARRIER GRADE



PLA-PBAT blown films COATED WITH PVOH and WAX

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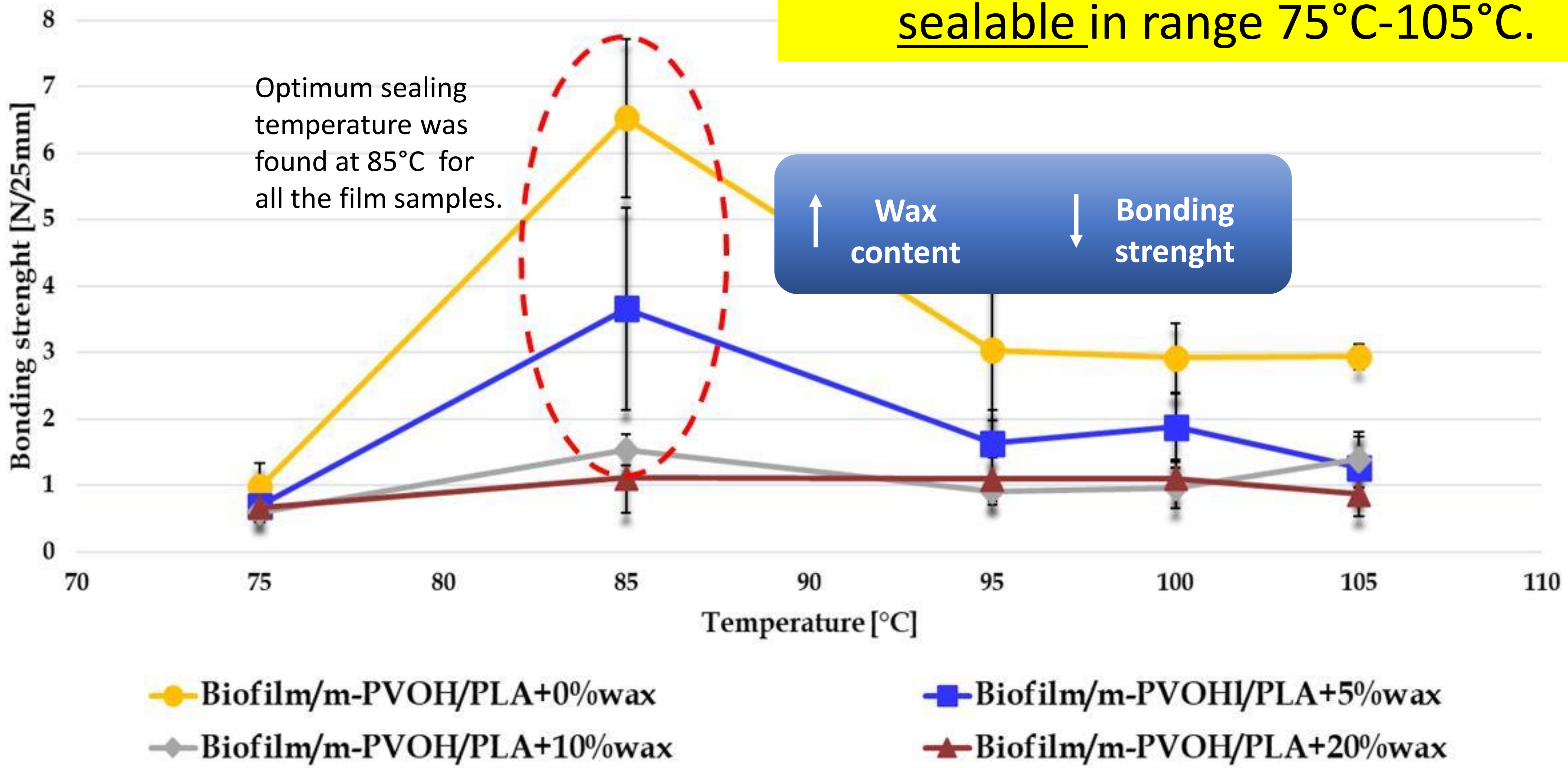
seal strenght

Biofilm and Biofilm/m-PVOH are not sealable in range 75°C-105°C.

Optimum sealing temperature was found at 85°C for all the film samples.

↑ Wax content ↓ Bonding strenght



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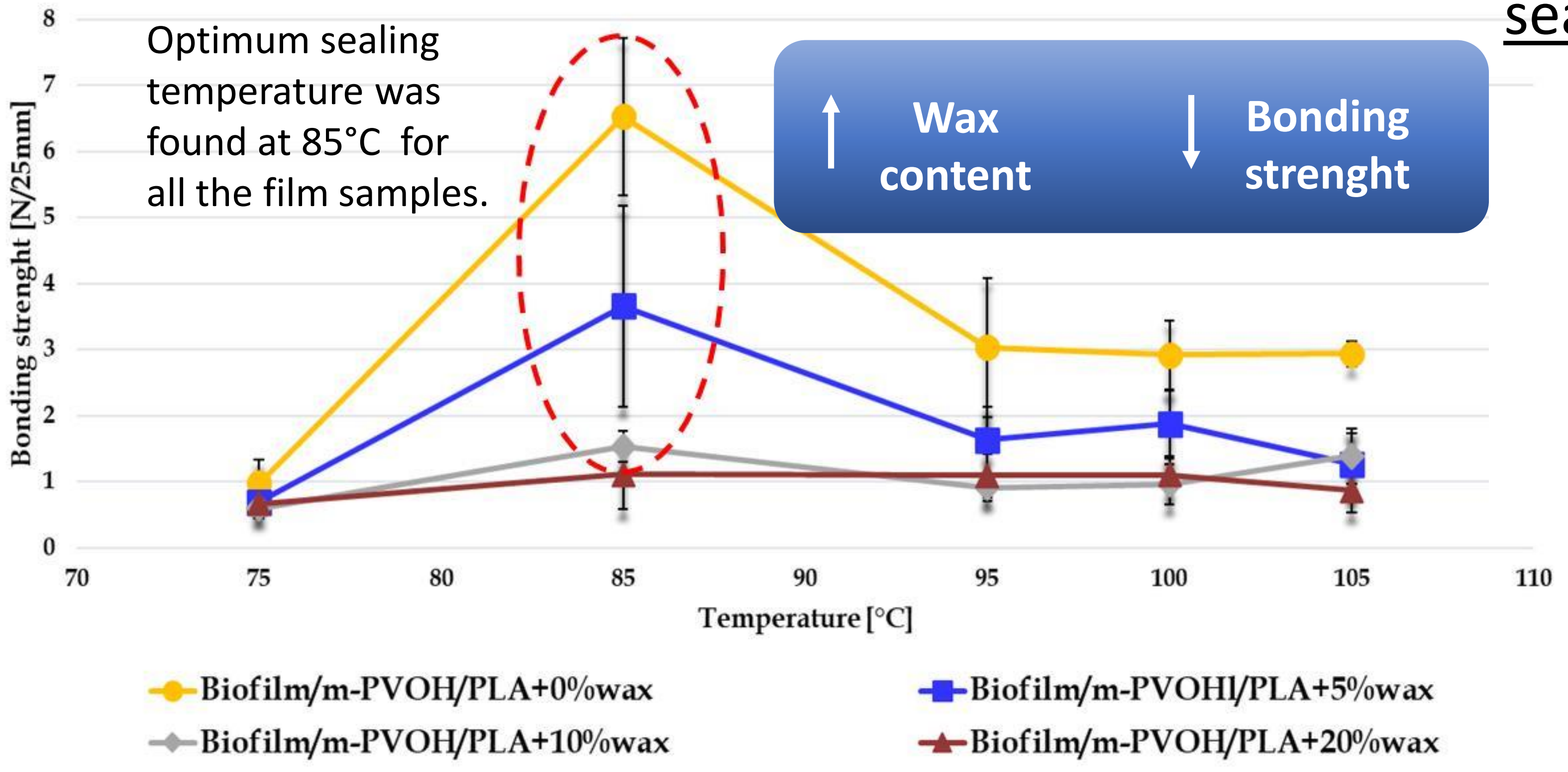

Biofilm and Biofilm/m-PVOH are <u>not sealable</u> in range 75°C-105°C.

The PLA coating layer provided additional sealability function to the multilayer films

- In all cases, seal adhesion remained still acceptable for the films application in food packaging *(Bamps et al., 2022; Iwasaki et al., 2015)*

PLA-PBAT blown films COATED WITH PVOH and WAX

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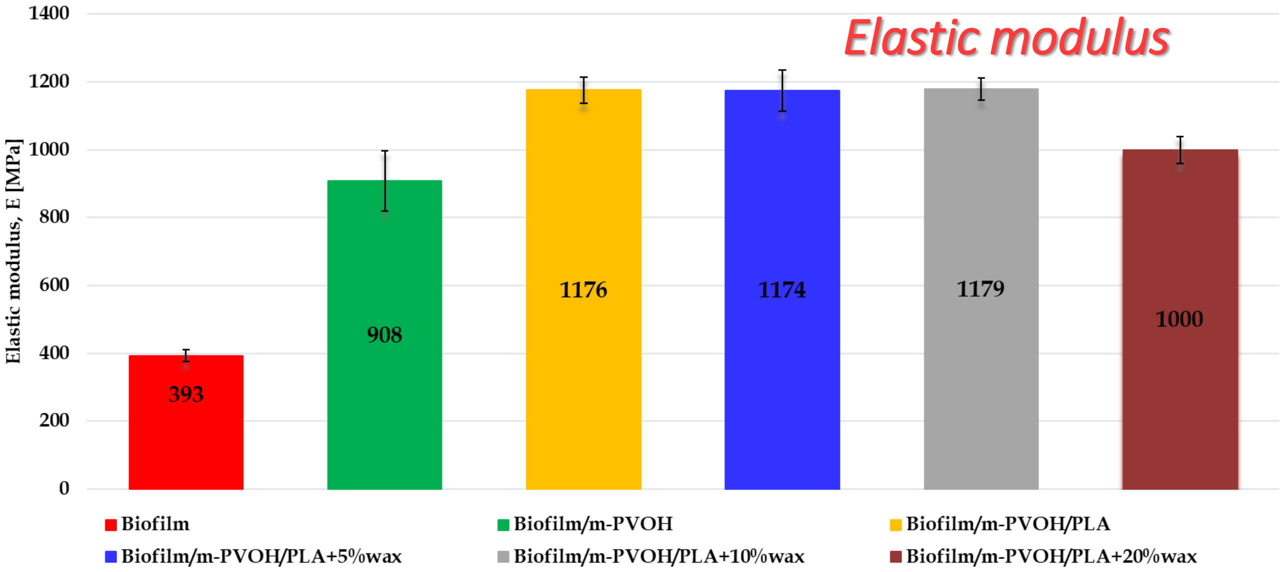
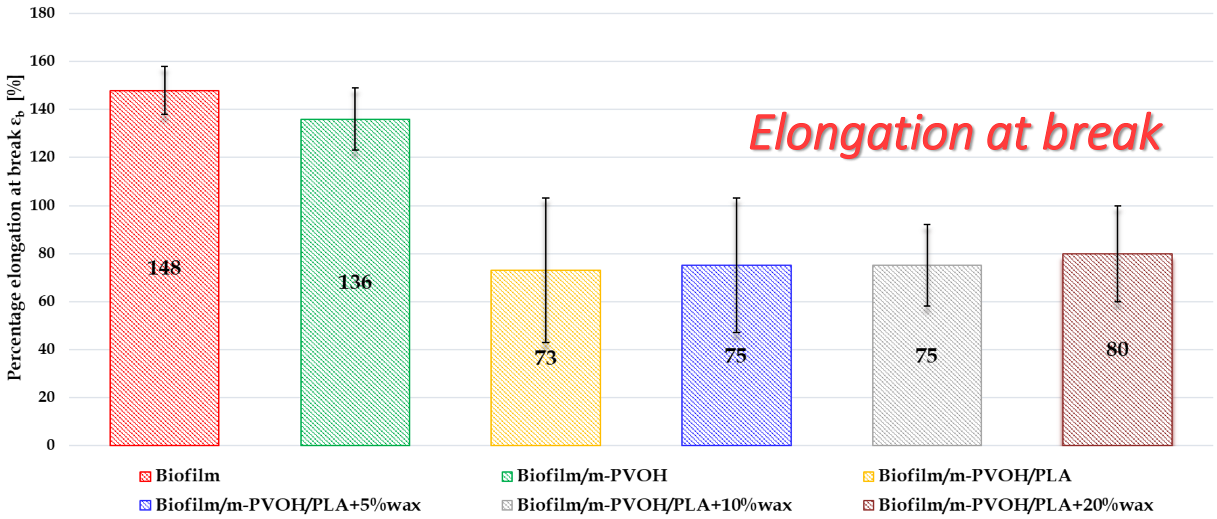
good balance between stiffness and ductility





- **Good ductility of Biofilm**
- **Consistent increase of its elastic modulus** after the deposition of both the m-PVOH and PLA layers, up to a maximum equal to 1179 MPa.
- **PLA coating layer decreases the films ductility** which remain still acceptable around 73%-80%.
- **No marked effects with wax incorporation** are noticeable: increasing EBS wax percentage elastic modulus and elongation at break are not aff

100% biodegradable multi-layers films

3 layers

POLYMERIC SUBSTRATE
Multicoated,
HIGH BARRIER

2° layer
1° layer
PLA/PBAT
BLOWN FILM

3 layers

CELLULOSIC SUBSTRATE
Multicoated paper,
HIGH BARRIER

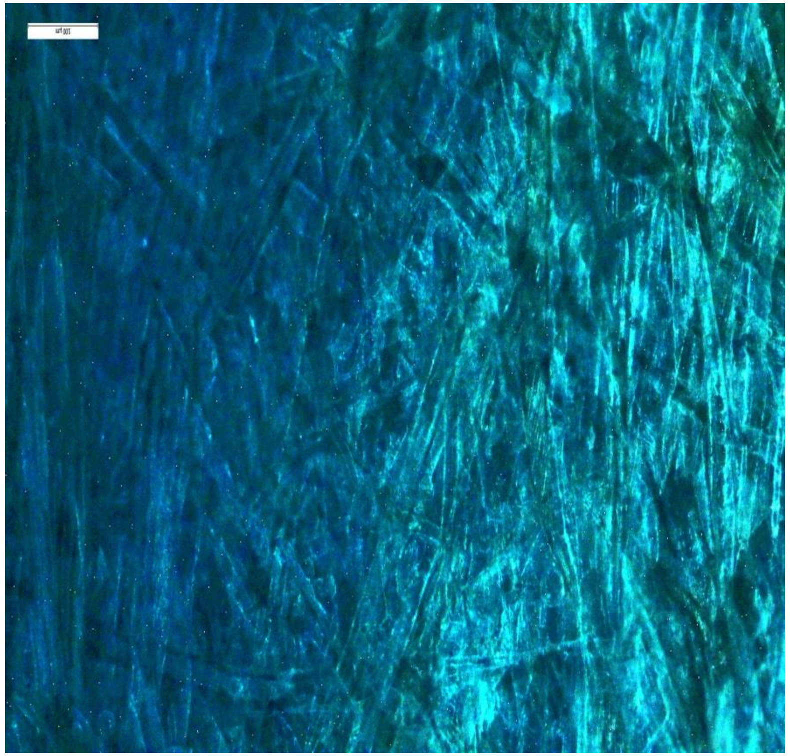
2° layer
1° layer
PAPER

2 layers

POLYMERIC SUBSTRATE
Coated,
ACTIVE BARRIER

1° layer
PBS/PVOH
BLOWN FILM

Multicoated paper



KRAFT PAPER COATED WITH m-PVOH and CARNAUBA WAX

Main limitations in the use of paper in the food packaging sector:

- High permeability
- Low resistance to oils and fats
- Hydrophilicity
- Non-sealable material

Proposed approach

deposition of a m-PVOH coating layer on the kraft paper substrate

- *Barrier properties*
- *Resistance to oils and greases*

additional layer of coating of wax/polymer blend

- *Sealing properties*
- *Hydrophobization*

KRAFT PAPER COATED WITH m-PVOH and POLYMER/CARNAUBA WAX

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MATERIALS

Kraft paper

High-quality KRAFT PAPER with a grammage of 100 g/m2;
Good mechanical strength;
Greater moisture resistance with respect other types of paper (richer in lignin).

m-PVOH

Exceval AQ-4104. Water soluble: easy to be removed in post consumer phase, High barrier properties, Reduced moisture sensitivity due to chemical modification

Mater Bi (EF05B)

- Flexible polymer matrix
- Excellent sealing properties (designed for shopper production)
- Hydrophilic

Carnauba wax

- Natural wax
- Highly hydrophobic
- Approved for use in contact with foodstuffs (cosmetics etc.)
- Odourless. tasteless
- Antioxidant properties are reported in literature

SAMPLES

KP/m-PVOH

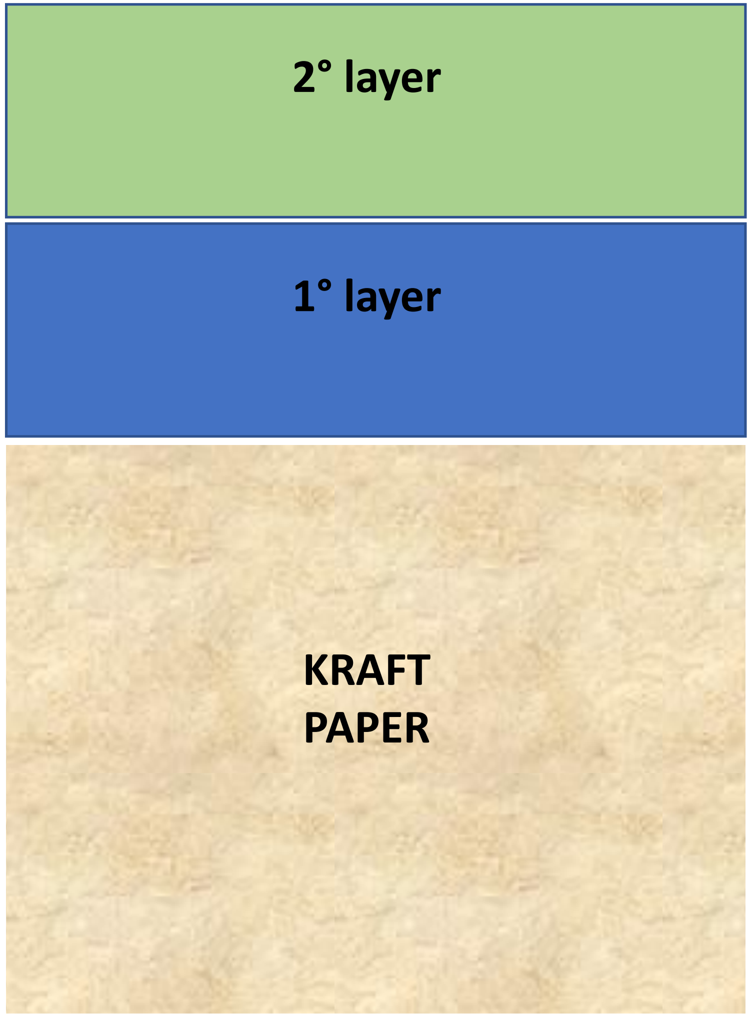
KP/m-PVOH/MB

KP/m-PVOH/MB+10%CW

KP/m-PVOH/MB+20%CW

KP/m-PVOH/MB+30%CW

KRAFT PAPER COATED WITH m-PVOH and POLYMER/CARNAUBA WAX



Carnauba wax in Mater-Bi

Exceval AQ-4104. Water soluble: easy to be removed in post consumer phase, High barrier properties,
Reduced moisture sensitivity due to chemical modification

High-quality KRAFT PAPER with a grammage of 100 g/m2;
Good mechanical strength;
Greater moisture resistance with respect other types of paper (richer in lignin).

KRAFT PAPER COATED WITH m-PVOH and POLYMER/CARNAUBA WAX

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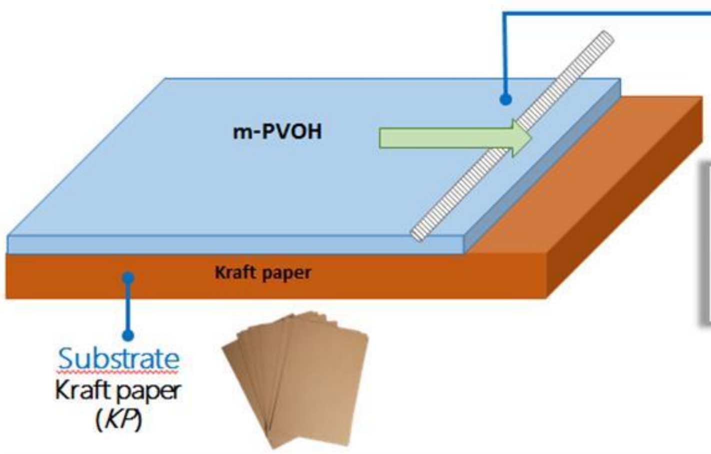
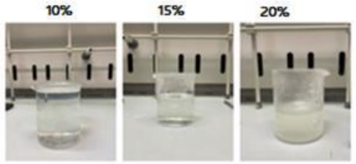
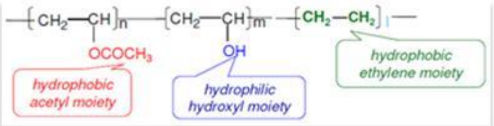
DESIGN AND REALIZATION OF THE COATED PAPER

The structures were realized through the deposition of water-based solutions having different percentages of PVOH (10%, 15%, 20% wt/wt) on the Kraft paper substate.





- ✓ Water soluble: easy to be removed in post consumer phase,
- ✓ High barrier properties,
- ✓ Reduced moisture sensitivity due to chemical modification

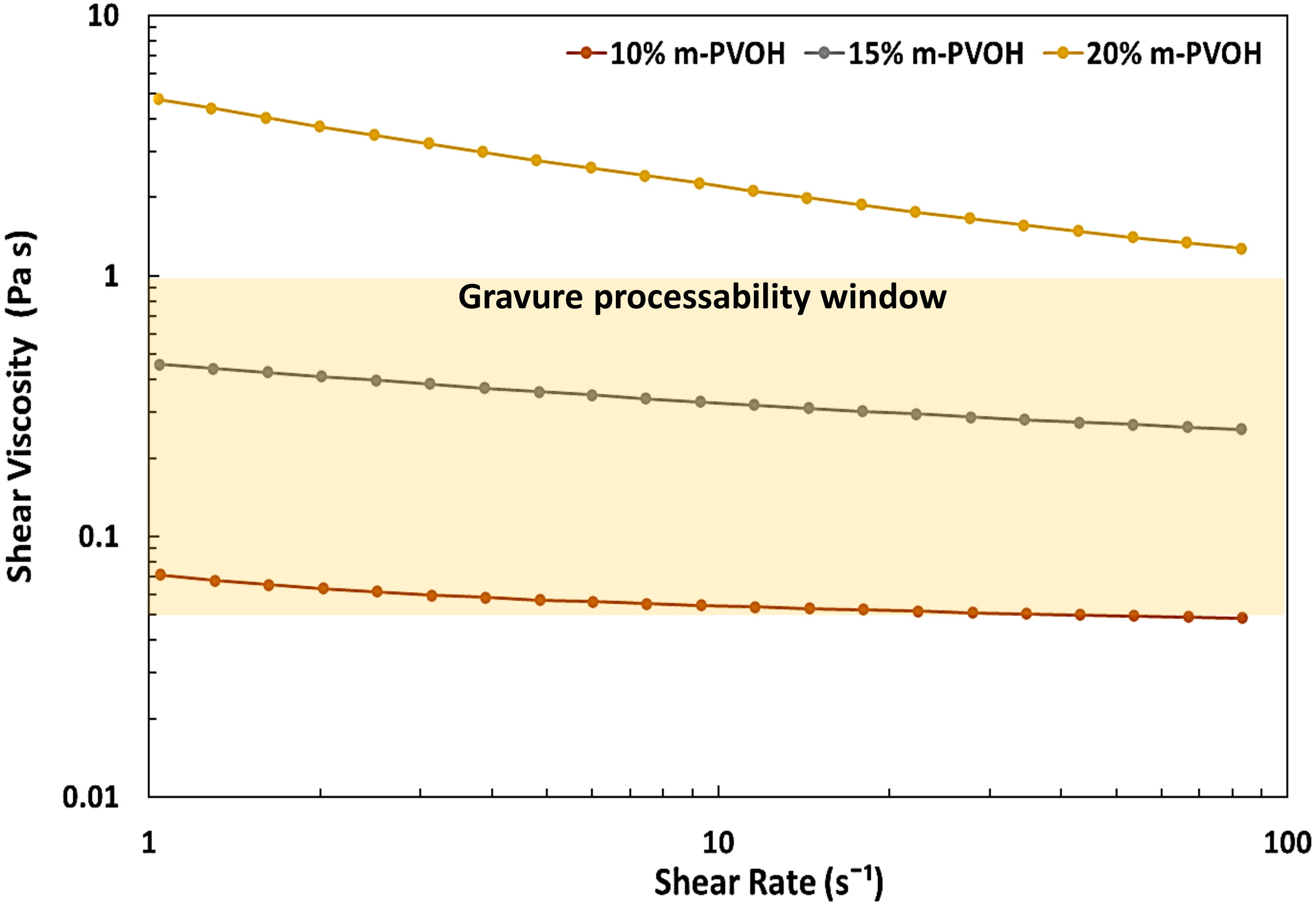


- ✓ High-quality KRAFT PAPER with a grammage of 100 g/m²;
- ✓ Good mechanical strength;
- ✓ Greater moisture resistance with respect other types of paper (richer in lignin).

Produced samples:

Sample	m-PVOH conc. [%w/w]	Grammage [g/m²]	Thickness [µm]
KP	-	104.3±0.8	151.3±2.8
KP/10% m-PVOH	10	113.2±1.5	158.3±3.6
KP/15% m-PVOH	15	116.0±1.8	159.6±1.7
KP/20% m-PVOH	20	121.3±2	162.0±2.2

KRAFT PAPER COATED WITH m-PVOH and POLYMER/CARNAUBA WAX



Why 15% m-PVOH?

- Is completely within the viscosity range of the process that we can reproduce with the hand coater (gravure).
- The overall properties of the KP/15% mPVOH sample are balanced .

Printing method	Viscosity range (Pa s)
Piezo Inkjet	0.005–0.03
Gravure	0.05–1.5
Flexography	0.05-0.5
Screen	1-10
Offset	40-100

[Ref : Kipphan Handbook print media] A Review of Gravure Coating Systems N. Kapur1. R. Hewson1. P.A. Sleigh2. J.L Summers1. H.M. Thompson1. S.J. Abbott3

KRAFT PAPER COATED WITH m-PVOH and POLYMER/CARNAUBA WAX

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Sample list: coating weights and thicknesses

EXCEVAL

C. WAX

Sample	C. Wax conc. [%w/w]	Grammage of the first coating [g/m^2]	Thickness of the first coating [μm]	Grammage of the second coating [g/m^2]	Thickness of the second coating [μm]
KP/m-PVOH	-	11.7±1.8	8.3±1.7	-	-
KP/m-PVOH/MB	-			19.5±2.5	8.4±2.2
KP/m-PVOH/MB+10%CW	10			20.7±2.8	12.7±1.5
KP/m-PVOH/MB+20%CW	20			22.0±2.7	13.1±4.8
KP/m-PVOH/MB+30%CW	30			25.6±4.3	14.7±2.2

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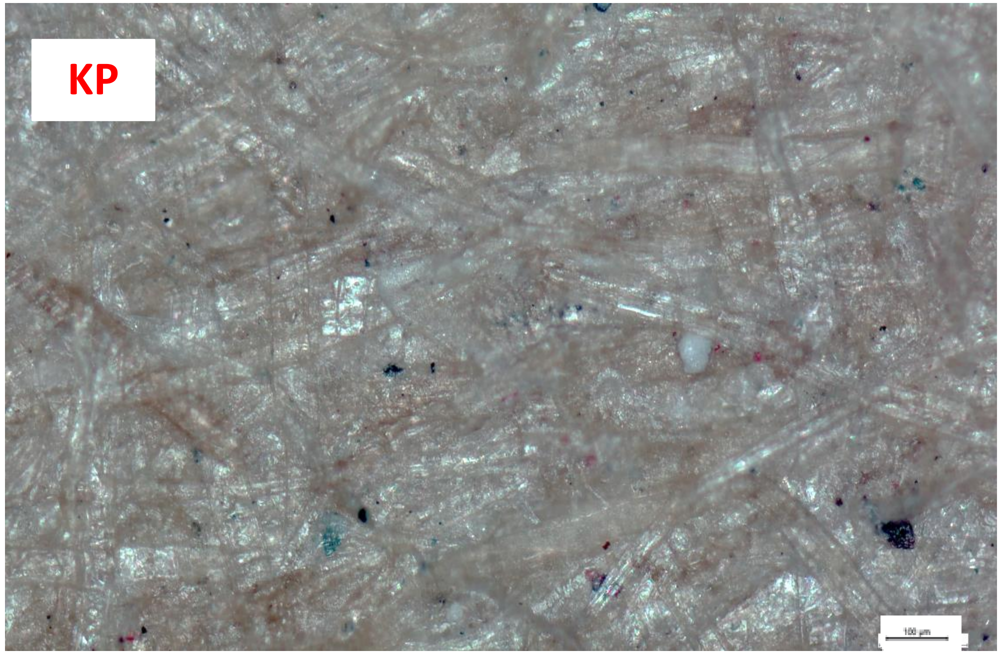
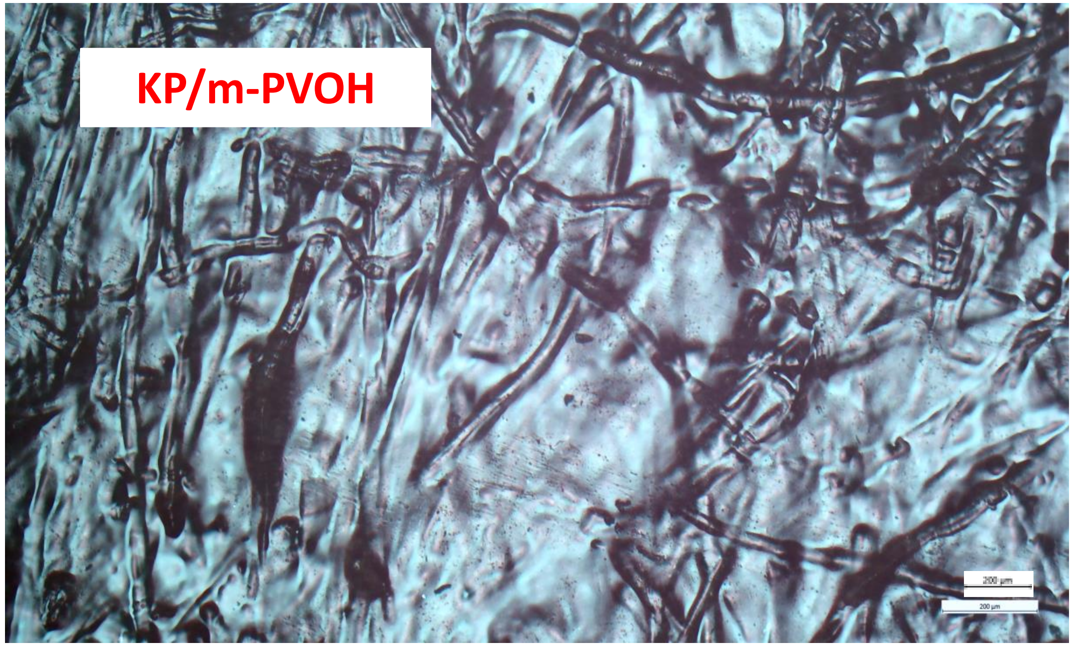
Optical microscopy





KRAFT PAPER COATED WITH m-PVOH and POLYMER/CARNAUBA WAX

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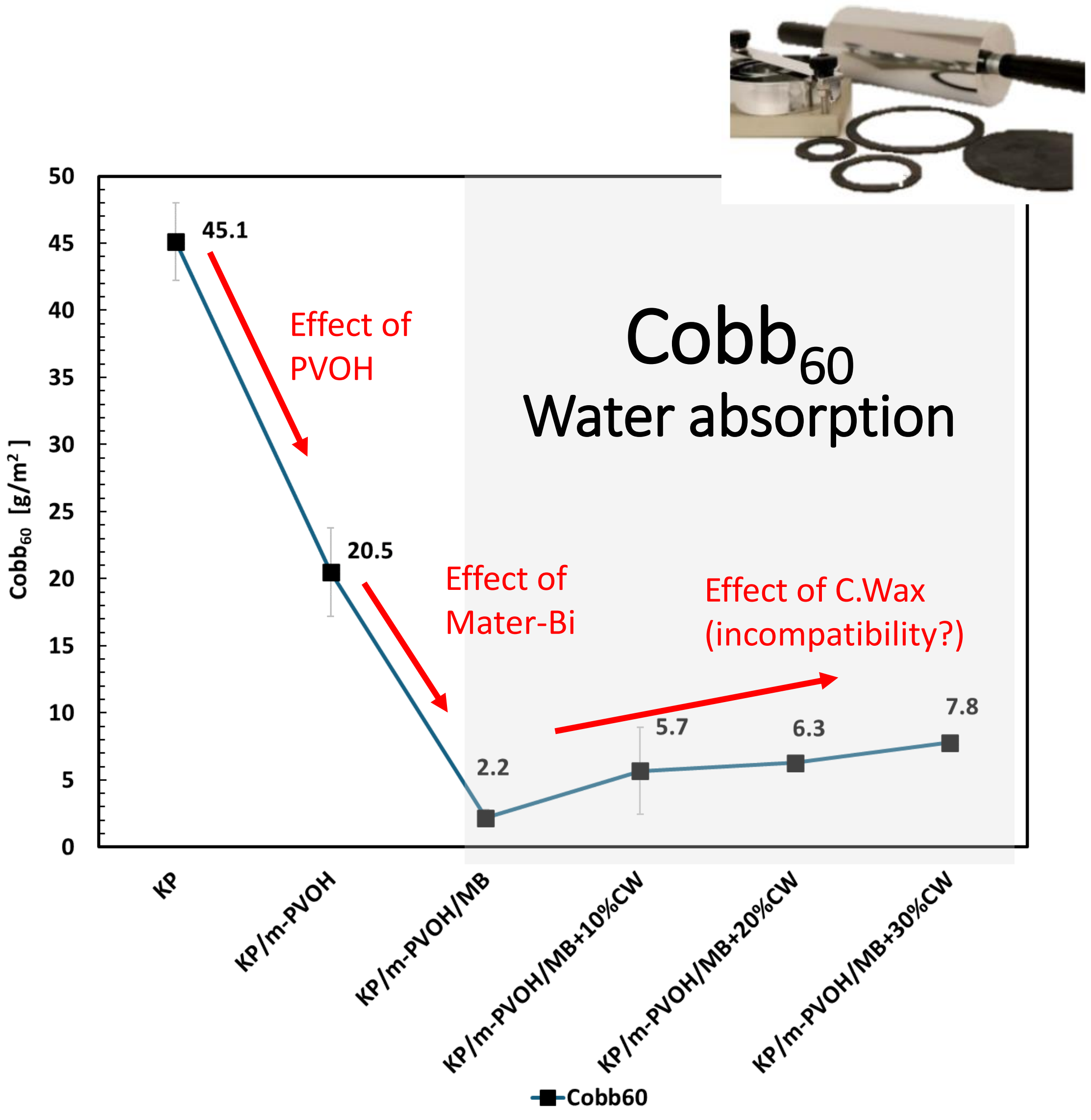
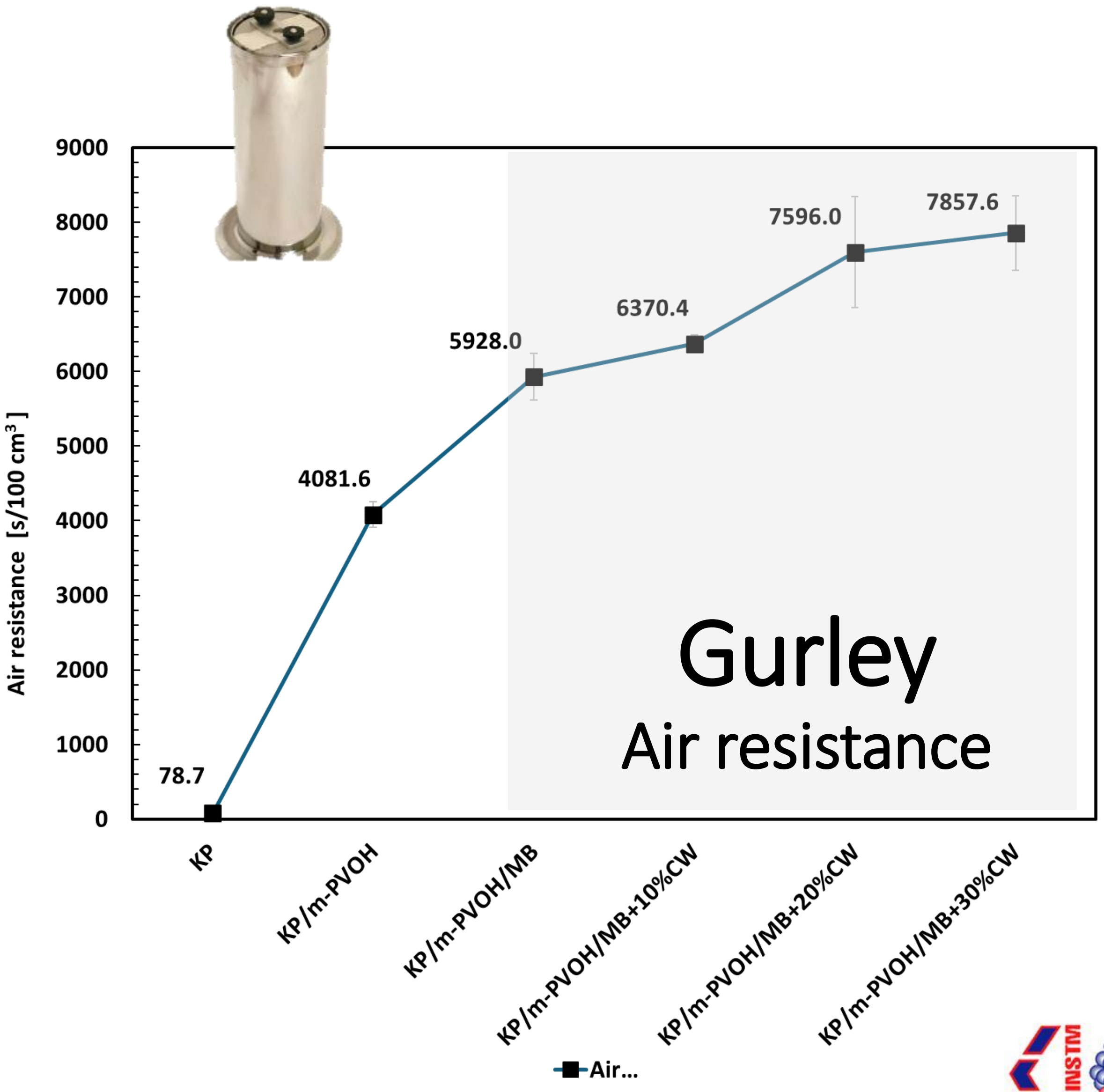


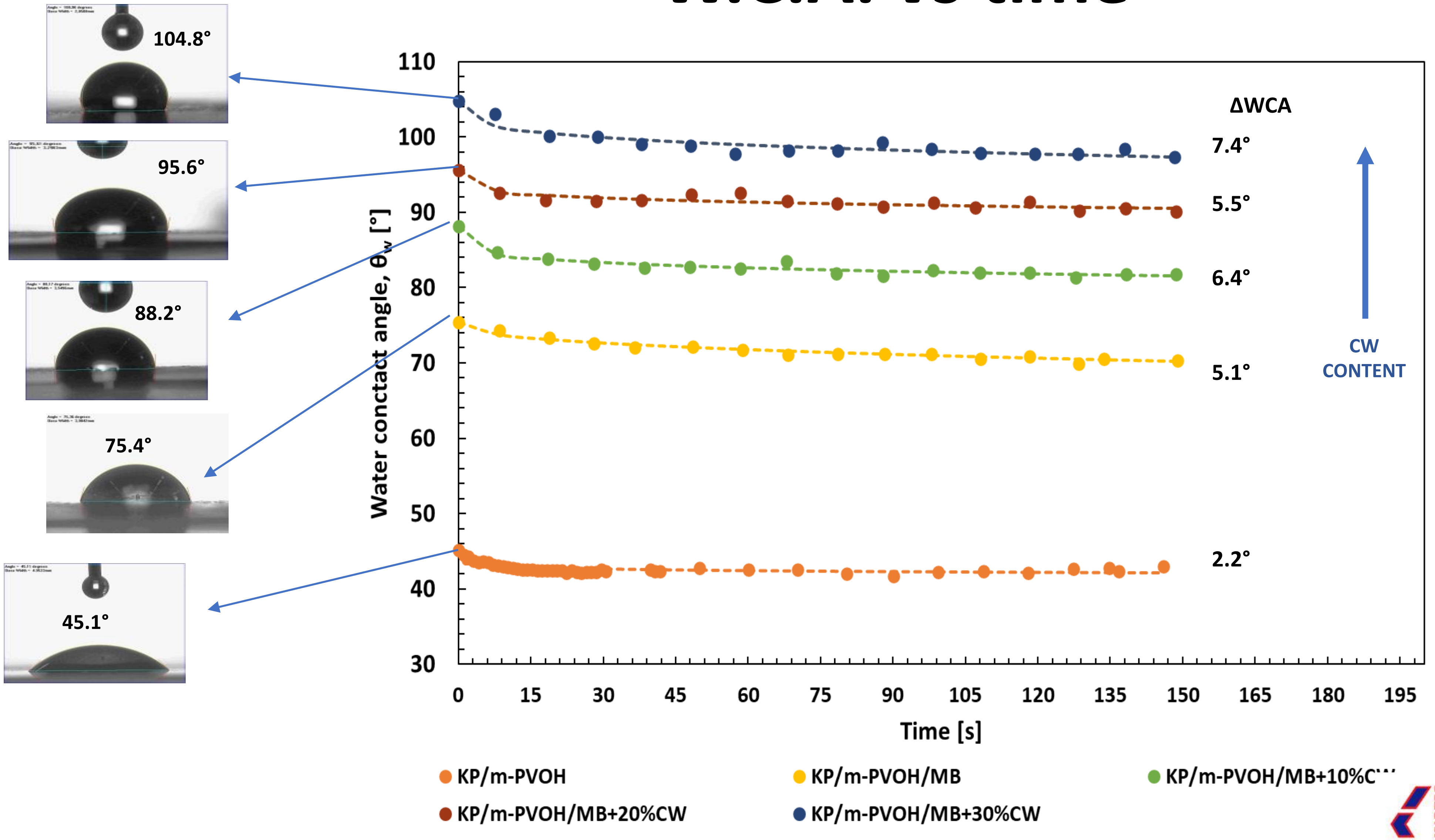


KRAFT PAPER COATED WITH m-PVOH and POLYMER/CARNAUBA WAX

W.C.A. vs time

Contact angle increases with the C. Wax

CW CONTENT



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Tensile in MD

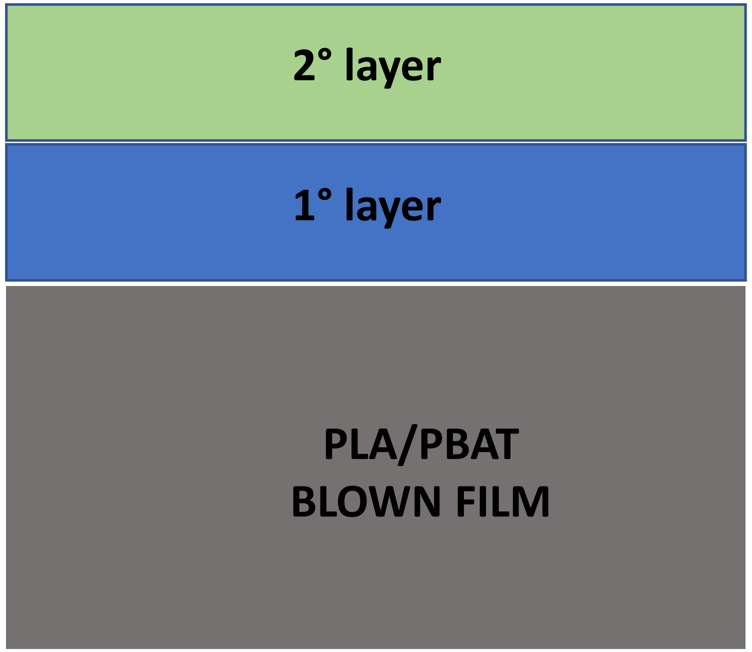
Sample	Tensile strength [kN/m]	Elongation at break [%]	Tensile Energy Absorption. TEA [J/m^2]
KP/m-PVOH	10.8±0.3	2.4±0.2	158.5±9.9
KP/m-PVOH/MB	11.7±0.7	2.8±0.2	202.2±27.3
KP/m-PVOH/MB+10%CW	11.4±0.7	2.8±0.2	199.1±27.0
KP/m-PVOH/MB+20%CW	11.3±0.9	2.7±0.2	187.4±28.9
KP/m-PVOH/MB+30%CW	11.3±0.8	2.6±0.2	180.0±23.4

- **MATER-BI improves mechanical properties: TS and elongation increase as does TEA**
- **The introduction of wax does not change the properties, which remain good and superior to the KP/mPVOH**

100% biodegradable multi-layers films

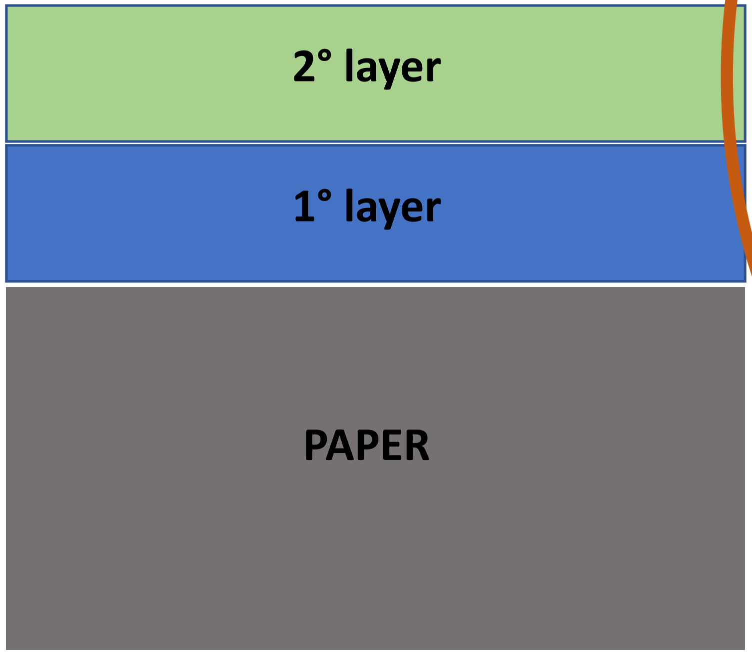
3 layers

POLYMERIC SUBSTRATE
Multicoated,
HIGH BARRIER



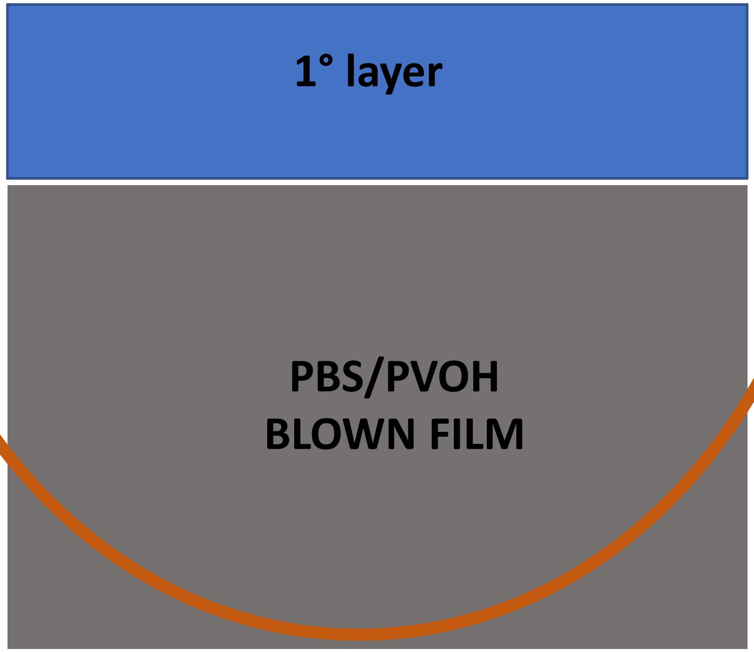
3 layers

CELLULOSIC SUBSTRATE
Multicoated paper,
HIGH BARRIER



2 layers

POLYMERIC SUBSTRATE
Coated,
ACTIVE BARRIER



Active antioxidant coating on biodegradable polymeric substrate

Biodegradable packaging with quercetin-based antioxidant coatings for fresh-cut preservation

Active antioxidant coating on biodegradable polymeric substrate

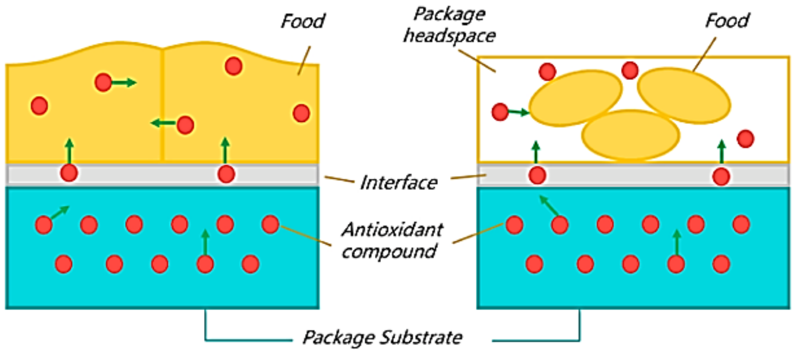
An **active food antioxidant packaging** system is able to :

- **Protect against oxidative damages** the food item,
- **Extend shelf-life** of sensitive foods,
- **Reduce food waste** avoiding economic losses.

Release of antioxidant molecules can be achieved through two methods:

(A)
Direct contact
Package-food system

(B)
Indirect contact
Package-headspace-food system



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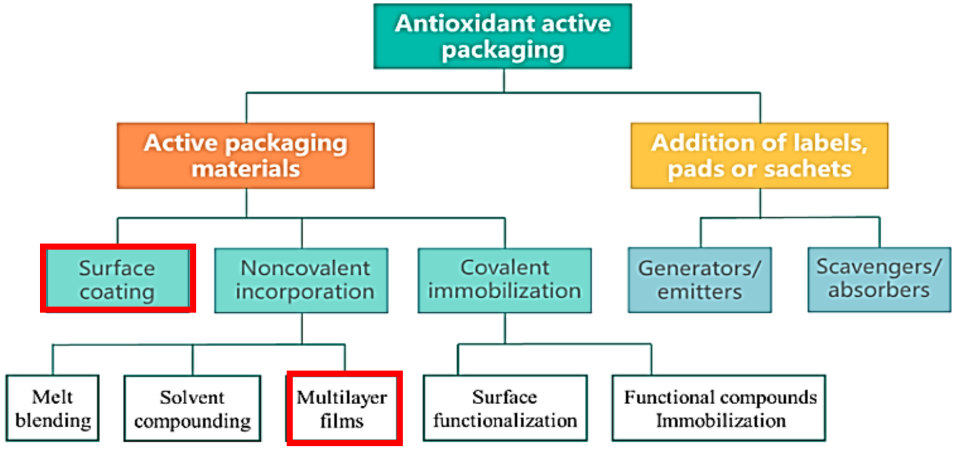
Antioxidant molecules can be added adopting different technological solutions:



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Active antioxidant coating on biodegradable polymeric substrate

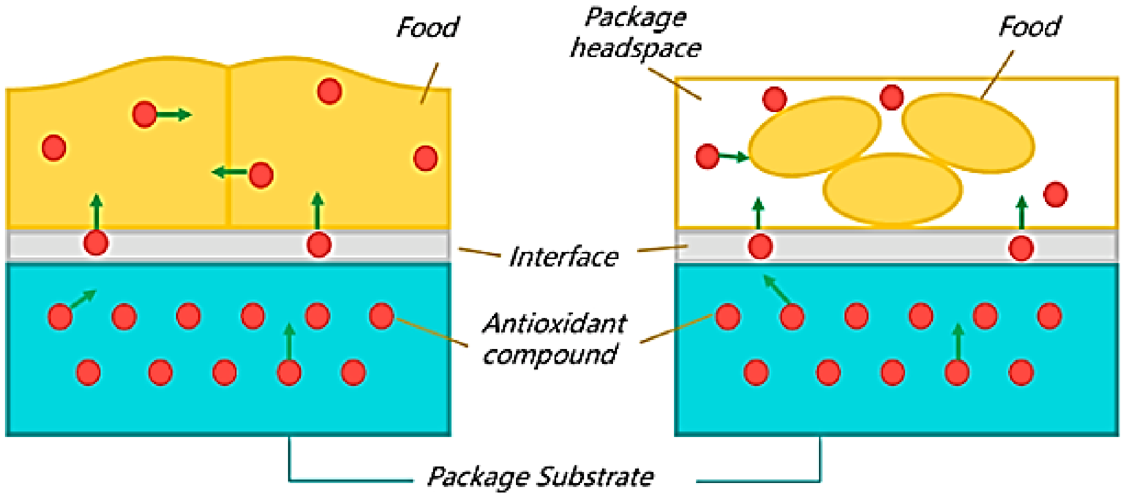
Release of antioxidant molecules can be achieved through two methods:

(A) **Direct contact**

Package-food system

(B) **Indirect contact**

Package-headspace-food system



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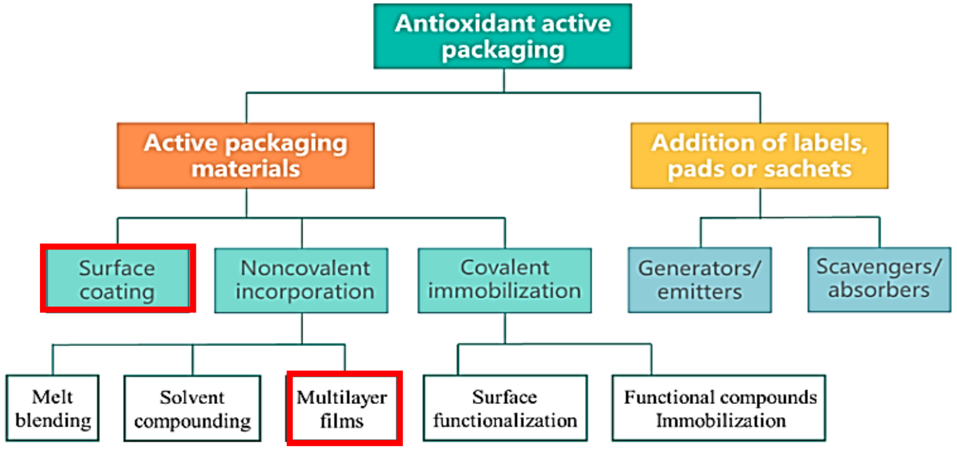

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Active antioxidant coating on biodegradable polymeric substrate

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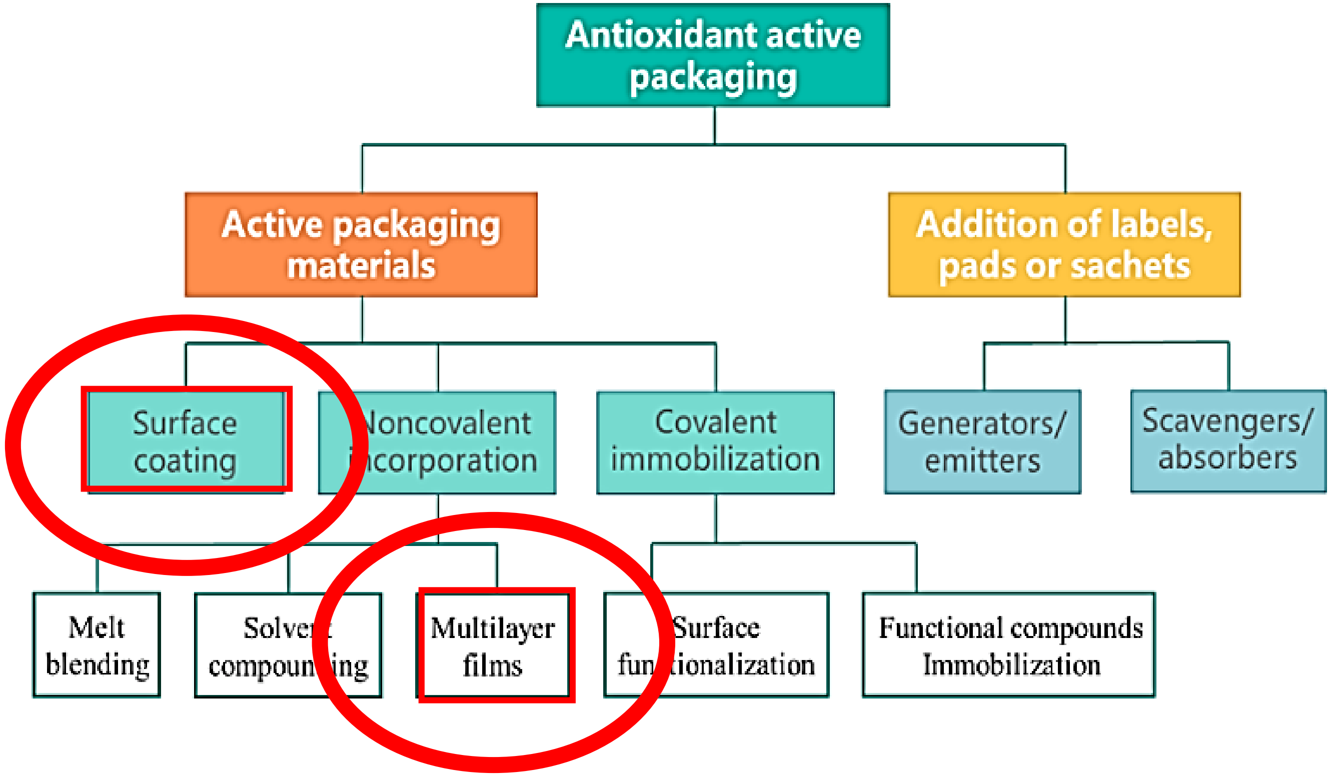

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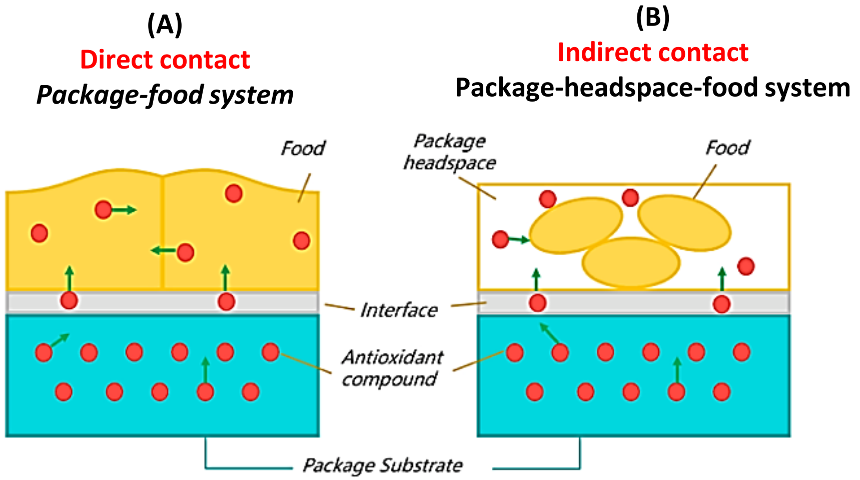

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Active antioxidant coating on biodegradable polymeric substrate

Quercetin is a naturally occurring yellow-colored plant phenolic (flavonoid) compound widely found in onions (10-30 mg/100 g), blueberries (15 mg/100g), asparagus (15-20 mg/100g) and many other crops.

Quercetine main biological activities:

Source: Swarup Roy, Parya Ezati, Ajahar Khan & Jong-Whan Rhim (2023): New opportunities and advances in quercetin-added functional packaging films for sustainable packaging applications: a mini-review, Critical Reviews in Food Science and Nutrition,

1. **Antioxidant activity**
   - **Quercetin's antioxidant capability** is six times that of commonly used Trolox *(Wang et al., 2016).*
2. **Safety and approval**
   - FDA-approved and **GRAS (Generally Recognized As Safe) for food applications** *(Roy and Rhim, 2021).*
3. **Versatility and stability**
   - **Stable compound** and **easily incorporated** into polymeric packages, mainly produced by **solution casting** and **electrospinning** *(Roy et al., 2023)*

Quercetin represents a good candidate for the development of functional food packaging films and/or coatings

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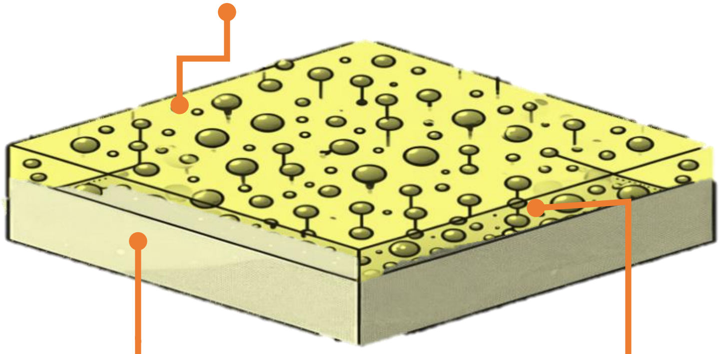
Active antioxidant coating on biodegradable polymeric substrate

MATERIALS

A blown film **(biodegradable substrate)** was functionalized through the application of an *antioxidant coating layer carried by PLA*

Antioxidant phase (QUE):
Quercetine (0%, 3%, 5%, 7% w/w_{PLA})



Bio-substrate (BS):
PBS/PVOH 80/20 wt% blown film

- ✓ Balanced mechanical and barrier properties
- ✓ **Fully biodegradable**
- ✓ **Not sealable**

Coating layer:
Amorphous PLA4060 + Tween 80 (1% w/w_{QUE})
SURFACTANT

- ✓ **Sealable layer**
- ✓ **Easy soluble to be removed**

Film sample	Que conc. [$\%w/w_{PLA}$]	Coating layer thick. [μm]	Total thick. [μm]
BS	-	-	35±3
BS/PLA	-	7±1	40±2
BS/PLA+3%QUE	3	6±2	39±3
BS/PLA+5%QUE	5	7±1	40±3
BS/PLA+7%QUE	7	8±1	41±2

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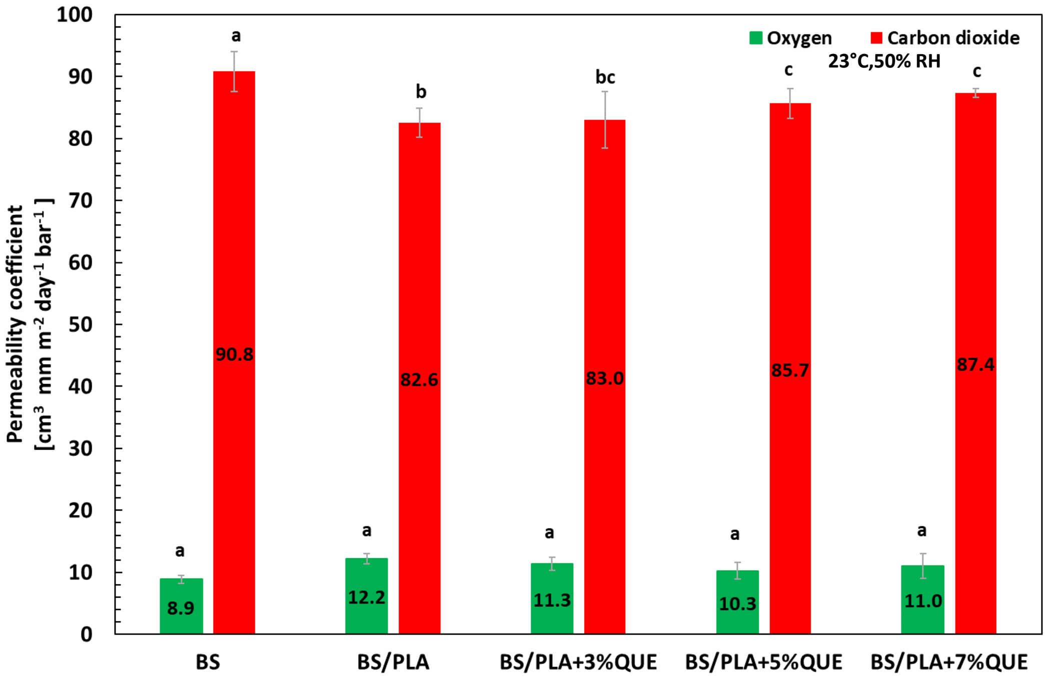
Active antioxidant coating on biodegradable polymeric substrate

O_2/CO_2 barrier properties and perm-selectivity



$$Permselectivity, \beta = \frac{P_{CO_2}(23°C\ 50\%RH)}{P_{O_2}(23°C\ 50\%RH)}$$

Film sample	Perm-selectivity P_{CO2}/P_{O2} [-]
BS	10.2
BS/PLA	6.8
BS/PLA+3%QUE	7.3
BS/PLA+5%QUE	8.3
BS/PLA+7%QUE	7.9

O_2 barrier

- **No significant difference between the oxygen permeabilities of the different film samples with and without the active layer:**
  - ✓ *PLA does not offer any additional O_2-transport resistance*; its PO_2 (~2300 cm^3 mm/m^2 d bar *(Turco et al., 2019)*) is approximately *3 o.o.m. higher than that of BS* (8.9 cm^3 mm/m^2 d bar).

CO_2 barrier

- **Carbon dioxide permeability slightly decreases by adding the PLA layer**
  - ✓ ***Amorphous PLA** has **a lower** PCO_2* (47,5 cm^3 mm/m^2 d bar *(Marano et al., 2022)*) than BS (90,8 cm^3 mm/m^2 d bar) offering an ***additional barrier***
- **Incorporation of QUE doesn't change the overall PCO_2**

In relation to the intended application:

Adequate O_2 and high CO_2 levels **have been proved to effectively control enzymatic browning, firmness and decay of *fresh-cut fruits and vegetables*** *(Rojas-Graü et al., 2008)*

The *optimal CO_2/O_2 perm-selectivity* ratio for fresh-cut produce packaging *depend on the specific respiration characteristics and gas requirements of the product.*

- ***A β value in the range 2.2-8.7 is typical for most films used in this application (Hussein et al., 2015).***

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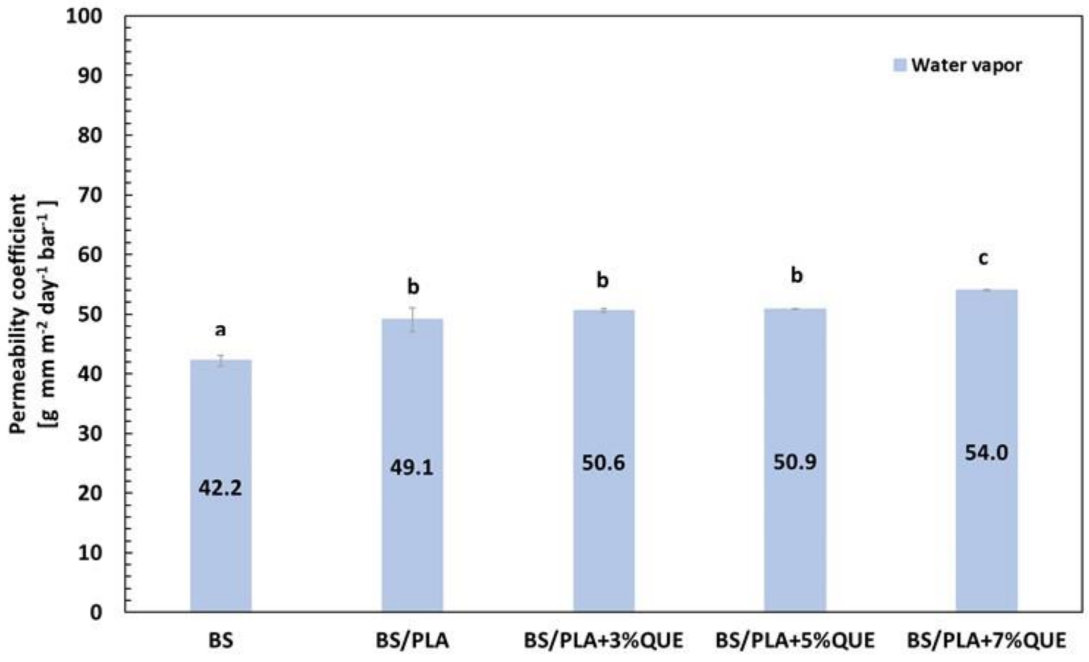
Water vapor barrier properties



Water vapor barrier

- **Pwv slightly increases by adding the PLA layer:**
  - ✓ ***High solubility of water vapor in PLA*** *(Barbato et al., 2023).*
- **Gradual slight increase of Pwv by increasing QUE concentration; more pronounced for BS/PLA+7%QUE:**
  - ✓ ***Quercetin's hydrophilicity attract water***, increasing water vapor transmission and enhancing film permeability as its content rises *(Roy et al., 2023).*

Classification of the biodegradable polymers depending on barrier perfomance (*J. Wang et al.,2018*)

Barrier grade	$P_{WV} \left[\frac{g\ mm}{m^2\ d\ bar}\right]$	Examples
High	<40	PGA
Medium	40-100	PHAs,
Low	100-300	Crystallized PLA, PPC
Poor	>300	Amorphous PLA, PBS, PBAT, PCL, PVOH

Developed multilayers are classified as MEDIUM water vapor barrier grade

In relation to the intended application:

***Moderate water vapor transpiration is crucial to prevent moisture buildup, condensation, and microbial growth in the packaging* thereby preserving the freshness of cut produce.**

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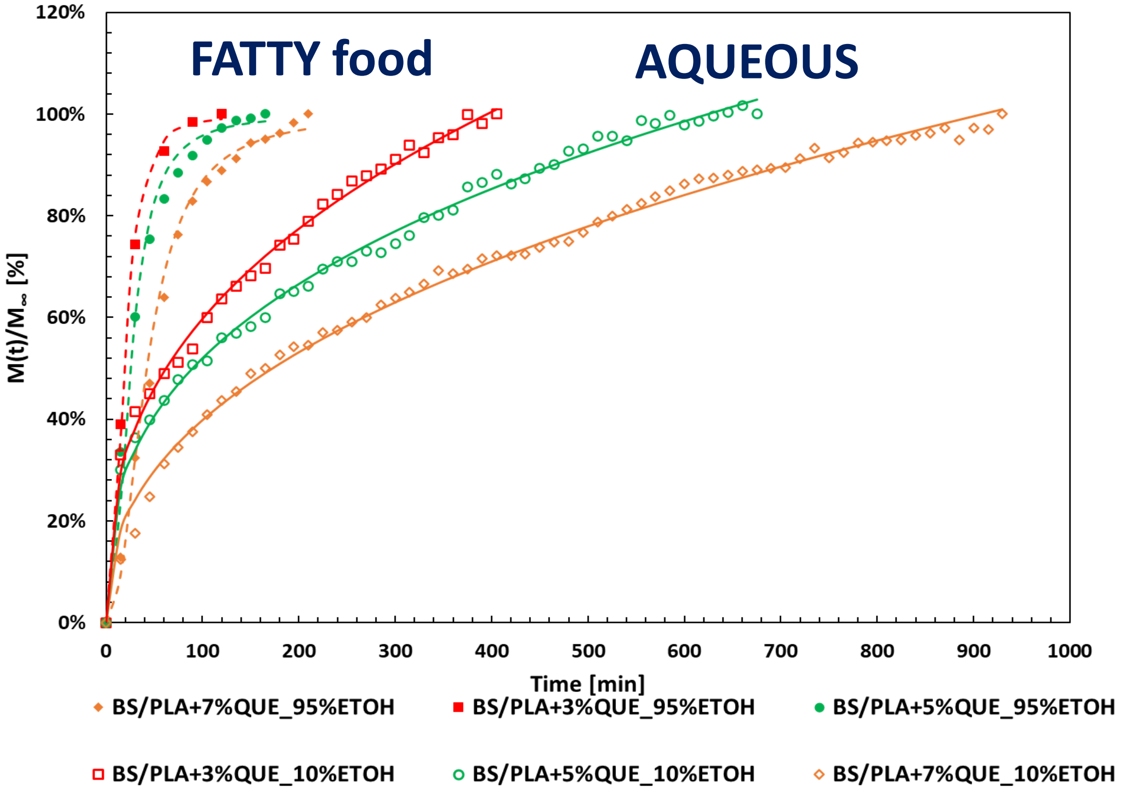
Release kinetics and antioxidant activity [1/2]



Test conditions:

- **Release media:** Ethanol 10% v/v (***AQUEOUS SIMULANT***) and ethanol 95% v/v (**FATTY SIMULANT)** *V*=100*mL**
- **Films Area:** 1 dm^2
- **Stored in darkness at room temperature**
- **Release kinetics by UV-Vis measurement** (λ=317 nm) **and calibration curve**
- **Antioxidant activity by DPPH test on the release medium at release plateau**

Sample	Exhaust. time [h]	Max amount released [mg/L]	DPPH scav. activity [%]
BS/PLA+3%QUE_95%ETOH	2	71.5	48.4
BS/PLA+5%QUE_95%ETOH	3	88.4	69.0
BS/PLA+7%QUE_95%ETOH	4	101.7	77.3
BS/PLA+3%QUE_10%ETOH	7	0.83	8.1
BS/PLA+5%QUE_10%ETOH	11	1.0	9.1
BS/PLA+7%QUE_10%ETOH	16	1.2	10.8

❑ **Effectiveness of antioxidant release** in both food simulants.

❑ **Release time and released amount** dependent by **QUE concentration**

Tunable release kinetics by varying the food matrix characteristics and the film composition.

*EC No 10/2011 on *Plastic materials and articles intended to come into contact with food. Official Journal of the European Union.*

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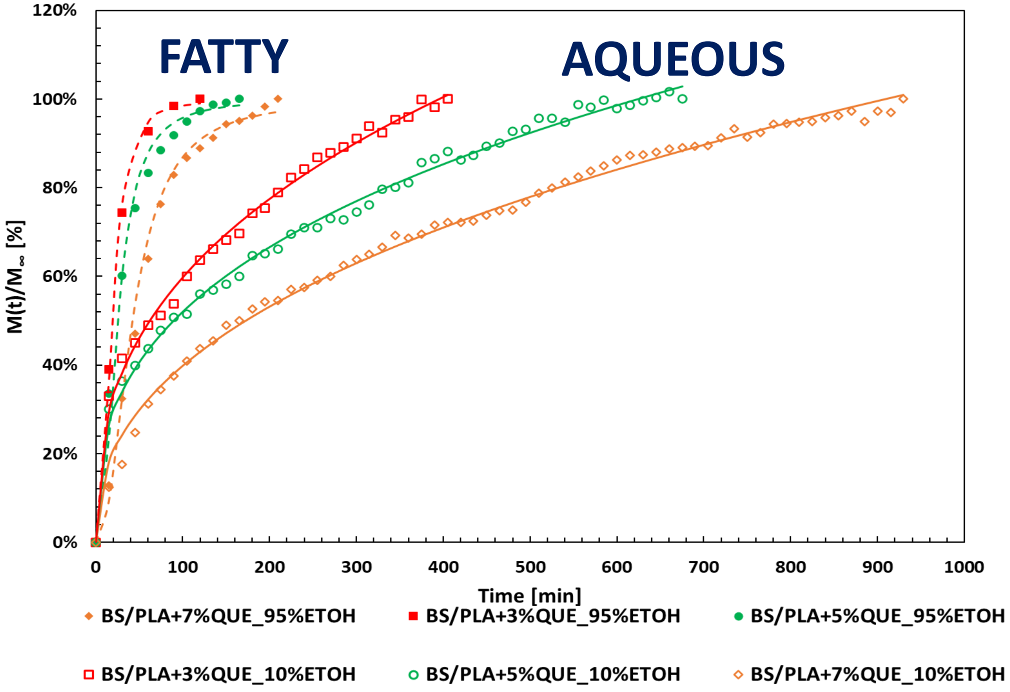
Release kinetics and antioxidant activity [2/2]



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BS/PLA+7%QUE_10%ETOH	16	1.2	10.8

IN FATTY FOOD SIMULANT:

- **Faster release kinetic**
- **Higher antioxidant release** (max. for BS/PLA+7%QUE: *101,7 mg/L*)
- **Higher antioxidant activity** (max. for BS/PLA+7%QUE: *77%*)

→ **Greater affinity of quercetin for fatty foods**

POSSIBLE APPLICATION

Sensitive foods with:

- **high respiration rates**
- **modest lipid content**
- **short-medium storage term**

→

Fresh-cut avocado

(Persea Americana)

15 g total lipids/ 100 g product*

*Dreher, M.L.; Cheng, F.W.; Ford, N.A. A Comprehensive Review of Hass Avocado Clinical Trials, Observational Studies, and Biological Mechanisms. Nutrients 2021, 13, 4376. https://doi.org/10.3390/nu13124376

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Preliminary shelf life tests: Visual appearance

Experimental Setup

- **Materials**:
  - 15 x 15 cm^2 Bags made of **BS/PLA** and **BS/PLA+7%QUE** films
  - **Unpackaged avocado slices (control samples)**
- **Sample configuration**:
  - Each bag contains two/three avocado slices
  - Average weight per bag: 42.9 ± 3.8 g
- **Storage conditions**:
  - Temperature: 4 ± 2°C (refrigerated)
  - Duration: 9 days
- **Analysis schedule**:
  - Conducted on **days 0, 1, 3, 6 and 9**
  - Three package replicates tested at each time point

- **CONTROL GROUP: Rapid browning along storage period and visible loss of weight and texture.**
- **BS/PLA GROUP: Visible darkening at the edges from day 3, weight and texture loss more moderate.**
- **BS/PLA+7%QUE GROUP: Only small signs of browning on day 6. Change towards reddish on day 9. Texture and moisture almost preserved.**

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Engineered Biodegradable Coatings on Cellulosic and Biopolymeric Substrates for Active, High Barrier Packaging Solutions

Conclusive remarks

Sustainable multilayer film based on passive and active materials were successfully produced by coating technique on both polymeric or cellulosic substrates

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Engineered Biodegradable Coatings on Cellulosic and Biopolymeric Substrates for Active, High Barrier Packaging Solutions

Conclusive remarks

It is possible to tailor both the substrate by using different biodegradable materials and the coatings, even in multiple steps, in order to achieve the requested performances.

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Engineered Biodegradable Coatings on Cellulosic and Biopolymeric Substrates for Active, High Barrier Packaging Solutions

Conclusive remarks

- ✓ **The use of a substrate based on polymeric blend allow to balance between ductility, and the stiffness, sealing ability**
- ✓ **Excellent oxygen barrier and water barrier properties provided by the m-PVOH and waxes**
- ✓ **Coating solutions: potential to serve as effective carriers for the controlled release of antioxidant agents in fruits with varying lipid concentrations.**

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Thank you for the kind attention

Luciano Di Maio

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