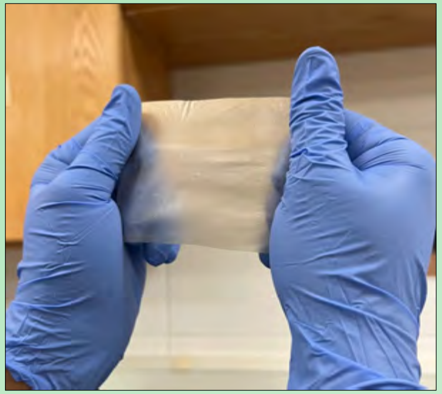
Alfalfa plant

Field residue

Cellulosic residue



Film

Fruit preservation

Biodegradation

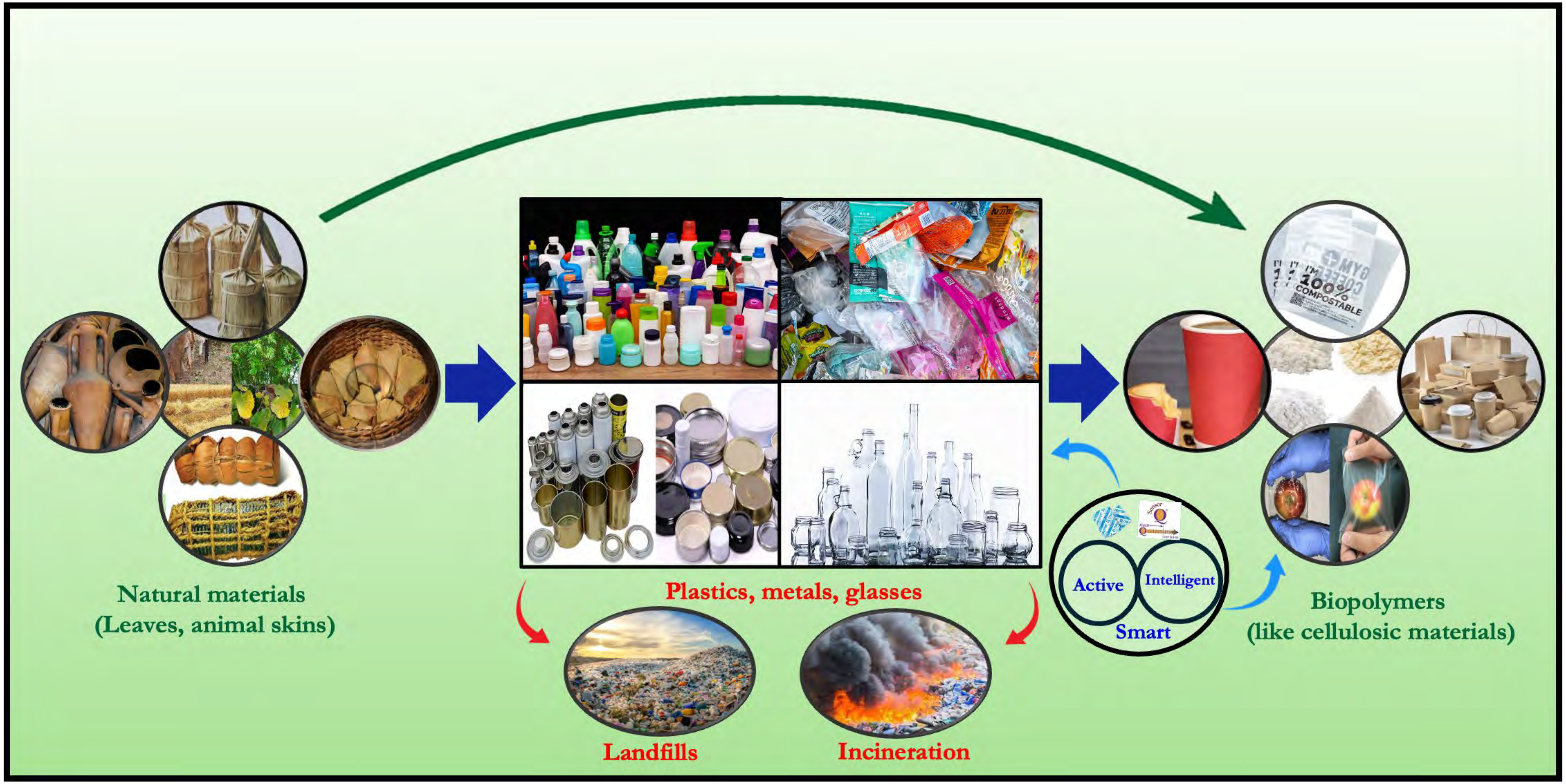
ALFALFA FIELD RESIDUE: A SUSTAINABLE RESOURCE FOR BIODEGRADABLE PACKAGING FILMS

South Dakota State University
Department of Dairy and Food Science

Sandeep Paudel and Srinivas Janaswamy
Srinivas.Janaswamy@sdstate.edu

NAAIC

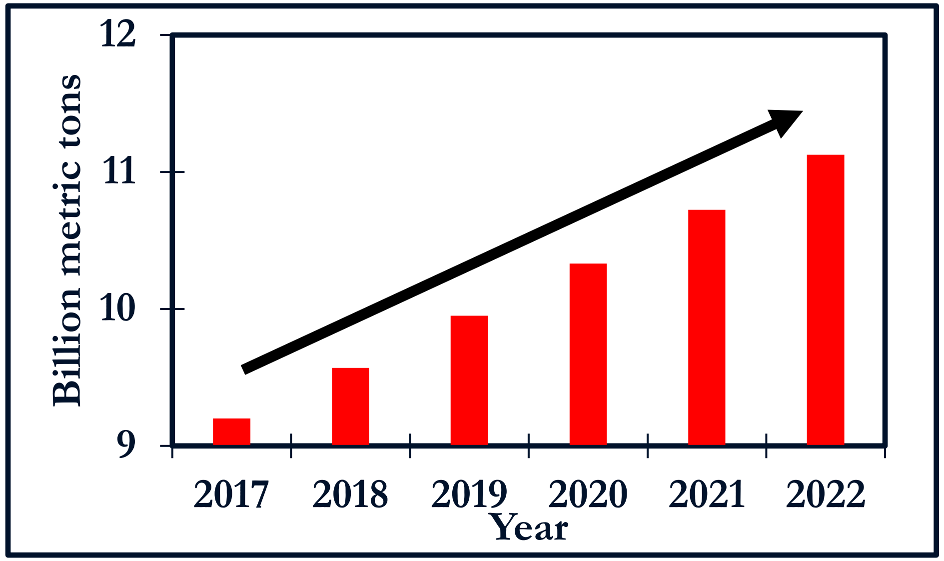
PACKAGING EVOLUTION



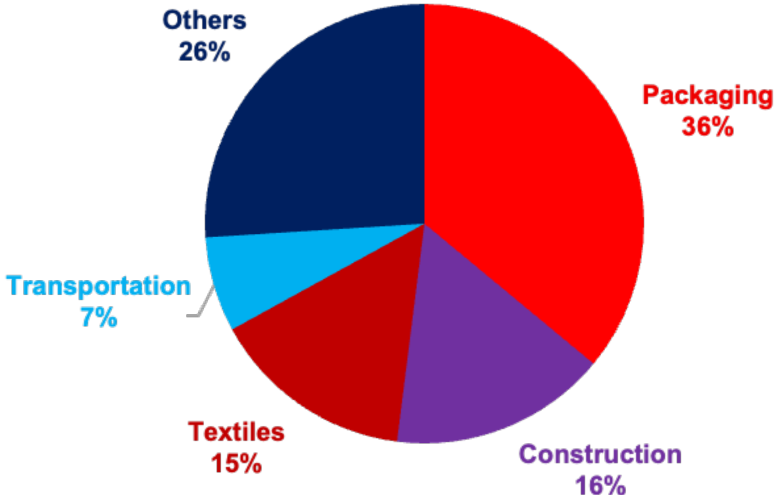
(Paudel et al., 2026a)

PLASTIC ADVANTAGES

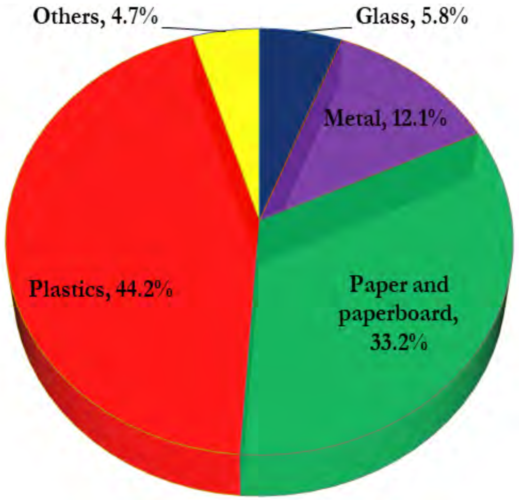
PLASTIC PRODUCTION AND USAGE



Cumulative plastic production



Plastic usage sector



Packaging materials

(Statista.com; Geyer et al., 2017; Fernandez, 2022)

EXISTING SOLUTIONS, APPROACH, AND LIMITATIONS

(Emmanuel et al., 2023)

- Paper packaging contributes to deforestation and leads to climate change
- Compostable materials need a special arrangement to compost them since they are not biodegradable
- Food sources like starch, proteins, lipids, and pectin are needed to feed the increasing population

LIGNOCELLULOSE: A PROMISING SOLUTION

- Cellulose is a linear polysaccharide composed of repeating β(1→4)-linked D-glucose units and serves as a primary structural component of plant cell walls
- Cellulose is the most abundant, renewable, non-toxic, mechanically robust, and excellent film-forming material, making it suitable for environmentally friendly packaging applications
- To avoid deforestation and maintain sustainability, cellulosic residue from agricultural biomass is a feasible option for developing biodegradable packaging films
- Herein, alfalfa biomass has been used as a test material

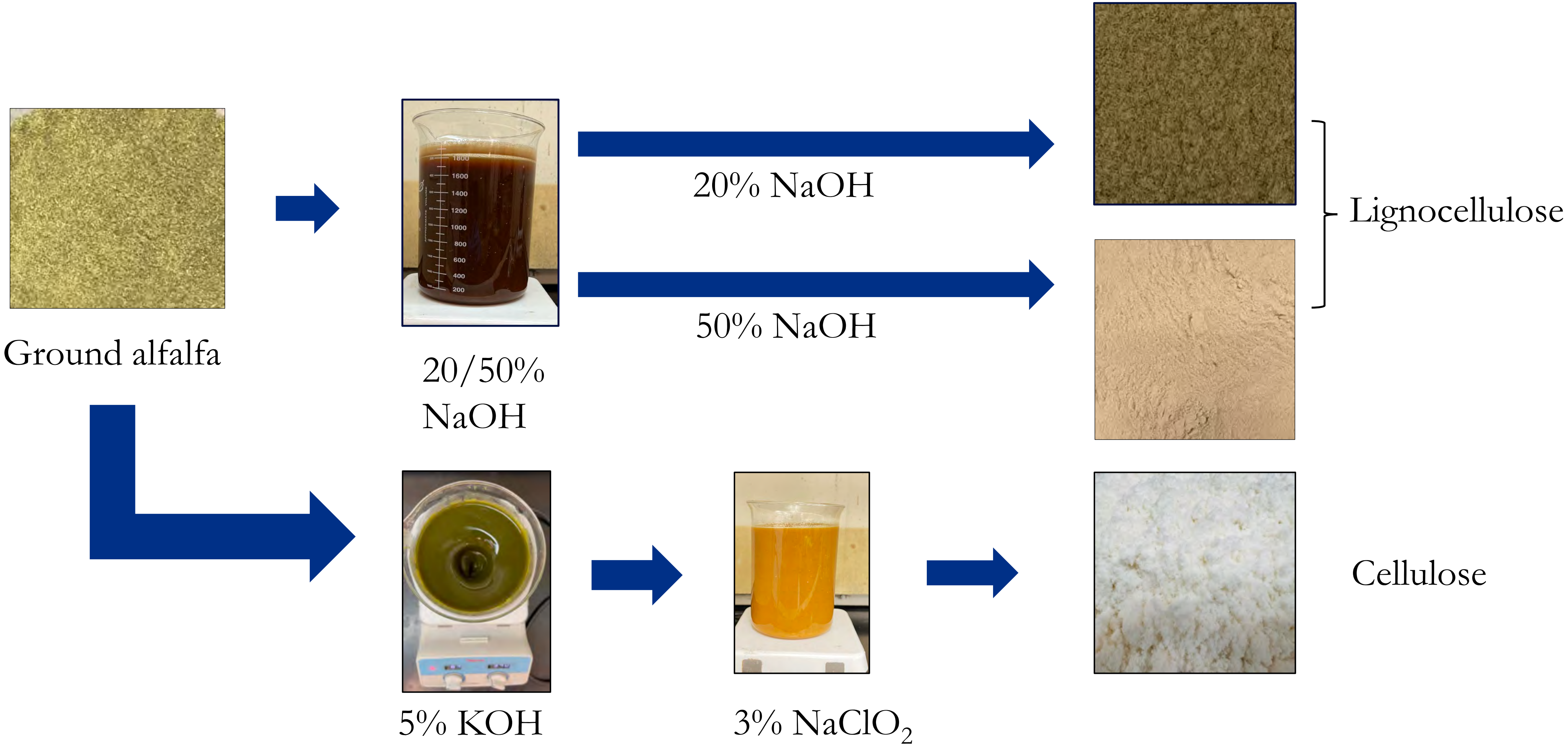
(Janaswamy et al., 2022)

LIGNOCELLULOSIC RESIDUE FROM ALFALFA BIOMASS

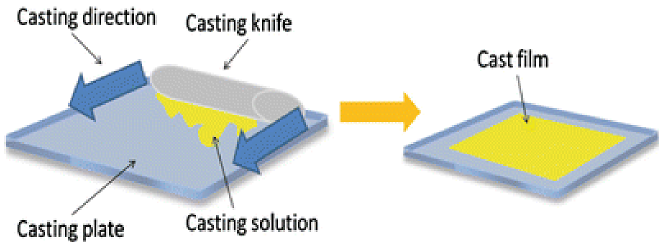


- Alfalfa (*Medicago sativa* L.) biomass is a viable material
- After the use of alfalfa as a forage, the field residue will be 25%
- Such field residue is around 68 million metric tons globally in 2023
- Its cellulose content is approximately 27%, making it a valuable resource
- Converting cellulose from 50% of the field residue will produce approximately 36,000 m^2 film (~$0.0178 per m^2), generating around $6 billion income for the farmers

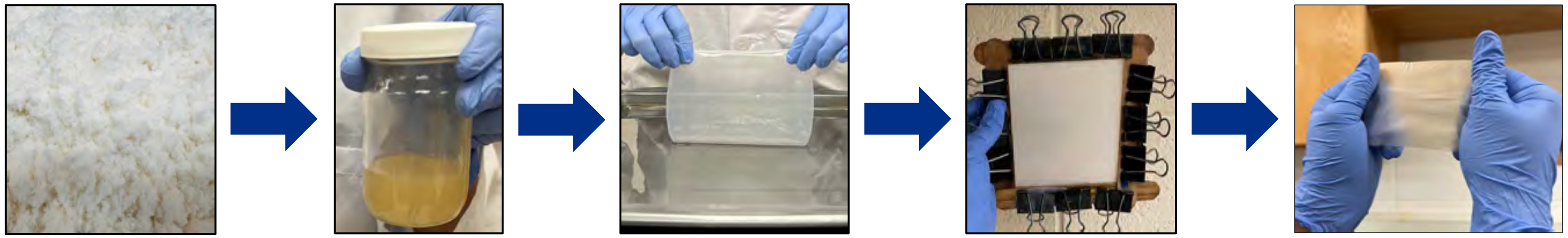
CELLULOSIC/LIGNOCELLULOSIC RESIDUE EXTRACTION

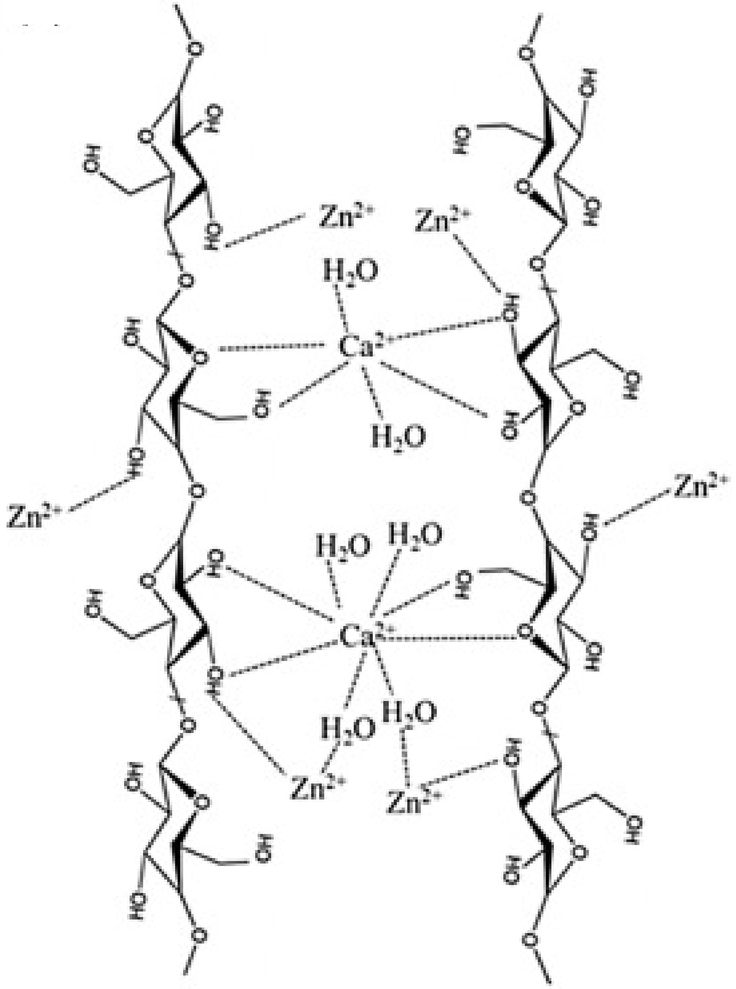


FILM PREPARATION



- Lignocellulose/Cellulose is swelled with distilled water
- Solubilized in a $ZnCl_2$ solution
- Crosslinked with Ca^{2+} ions and plasticized with sorbitol
- Lignocellulose/Cellulose solution is cast to form a film
- The film is regenerated using ethanol
- The film is framed, washed with distilled water, and dried





FILM OPTIMIZATION

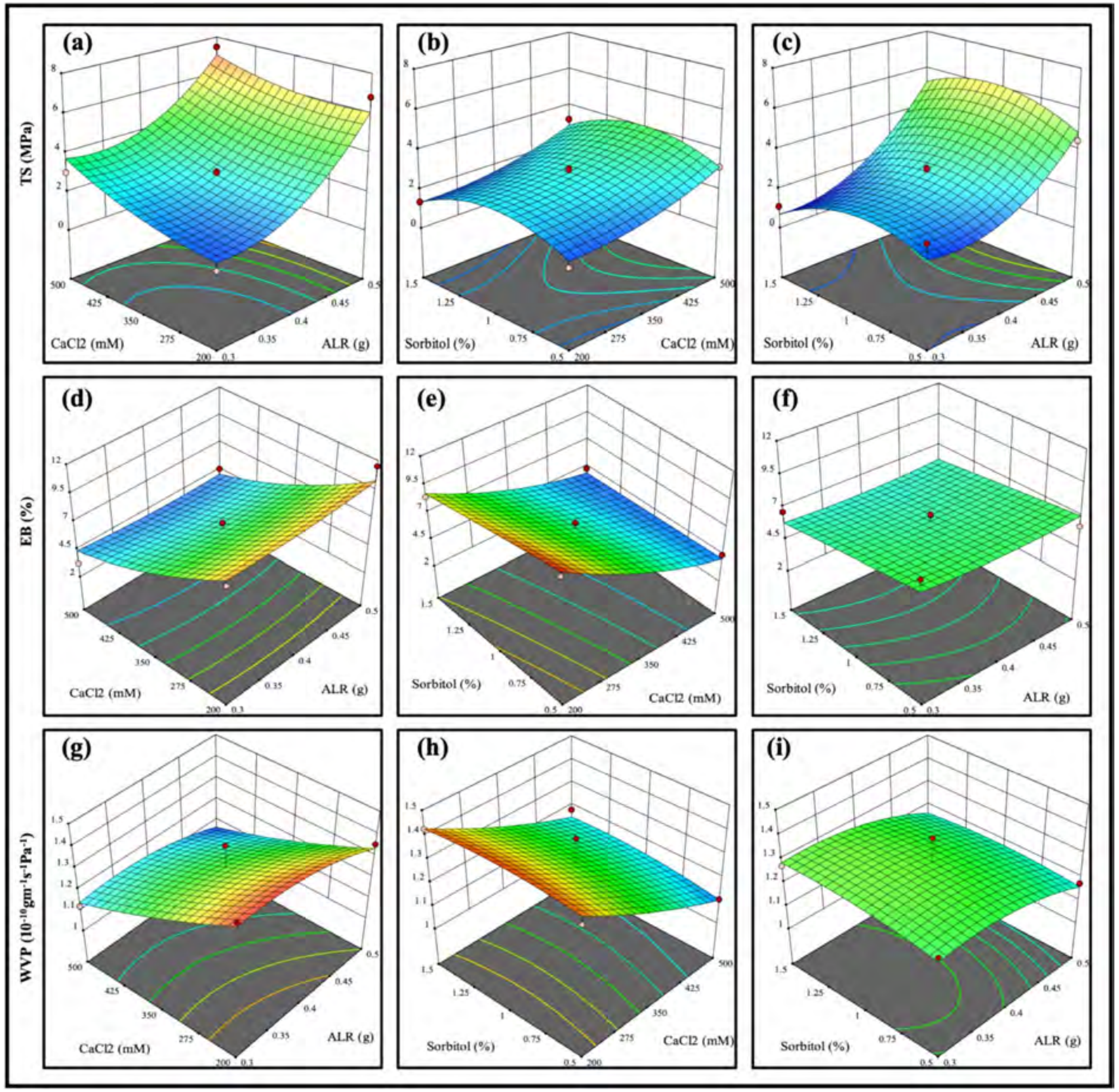
20% NaOH extracted lignocellulose

- Tensile strength:
  1.1-7.5 MPa
- Elongation at break:
  3.2-11.5%
- Water vapor permeability:
  $1.05\text{-}1.49 \times 10^{-10}$ g.m^{-1}.s^{-1}.Pa^{-1}

<u>Optimized condition</u>

- Alfalfa lignocellulose: 0.5 g
- $CaCl_2$: 263.5 mM
- Sorbitol: 0.84%

- Tensile strength: 5.7 MPa
- Elongation at break: 8.3%
- Water vapor permeability: 1.4×10^{-10} g.m^{-1}.s^{-1}.Pa^{-1}



FILM OPTIMIZATION…

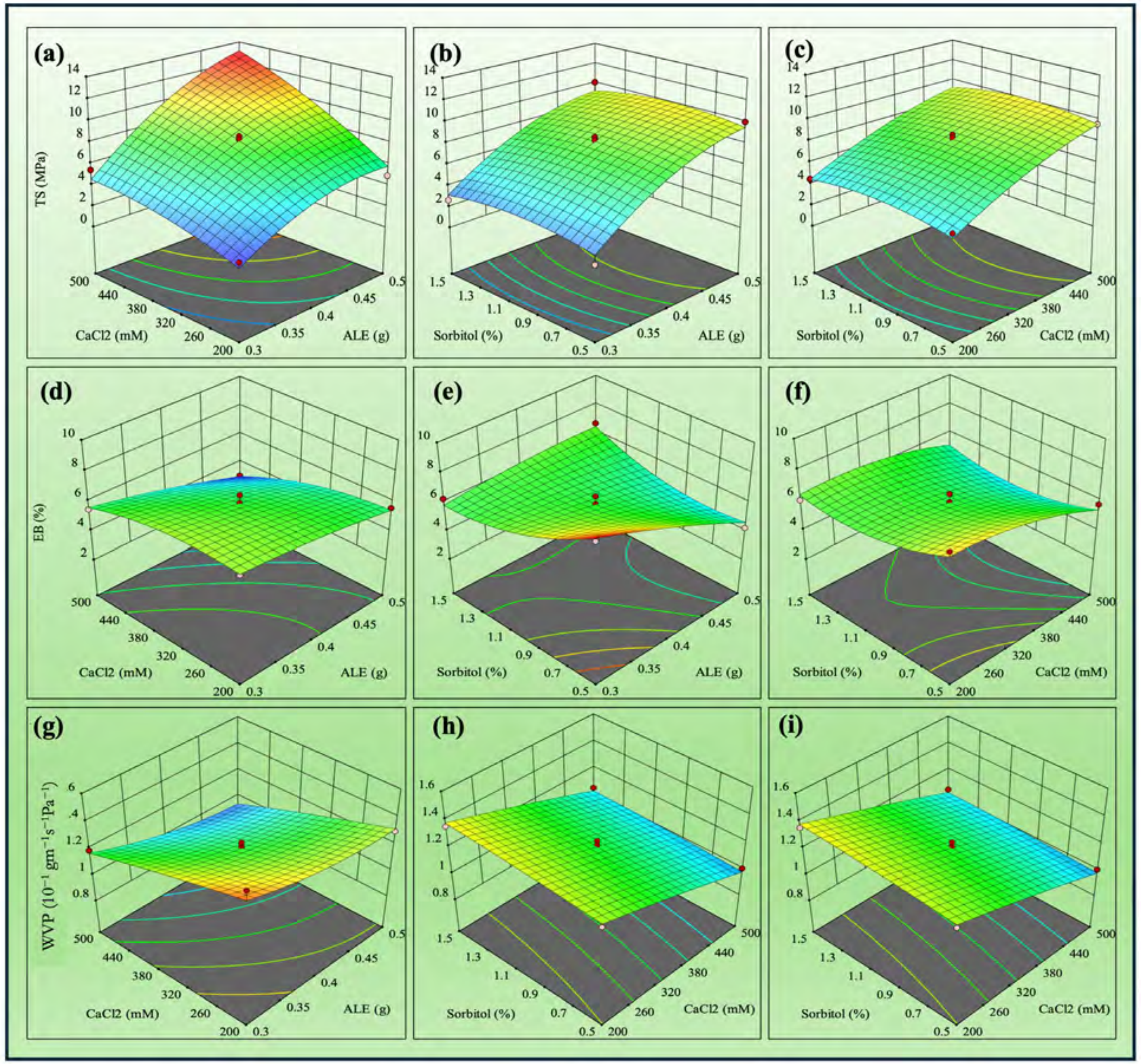
50% NaOH extracted lignocellulose

- Tensile strength:
  2.2-12.6 MPa
- Elongation at break:
  2.9-9.1%
- Water vapor permeability:
  $0.9\text{-}1.6 \times 10^{-10}$ $g.m^{-1}.s^{-1}.Pa^{-1}$

Optimized condition

- Alfalfa lignocellulose: 0.5 g
- $CaCl_2$: 453.8 mM
- Sorbitol: 1.5%

- Tensile strength: 11.2 MPa
- Elongation at break: 5.8%
- Water vapor permeability: 1.2×10^{-10} $g.m^{-1}.s^{-1}.Pa^{-1}$



FILM OPTIMIZATION…

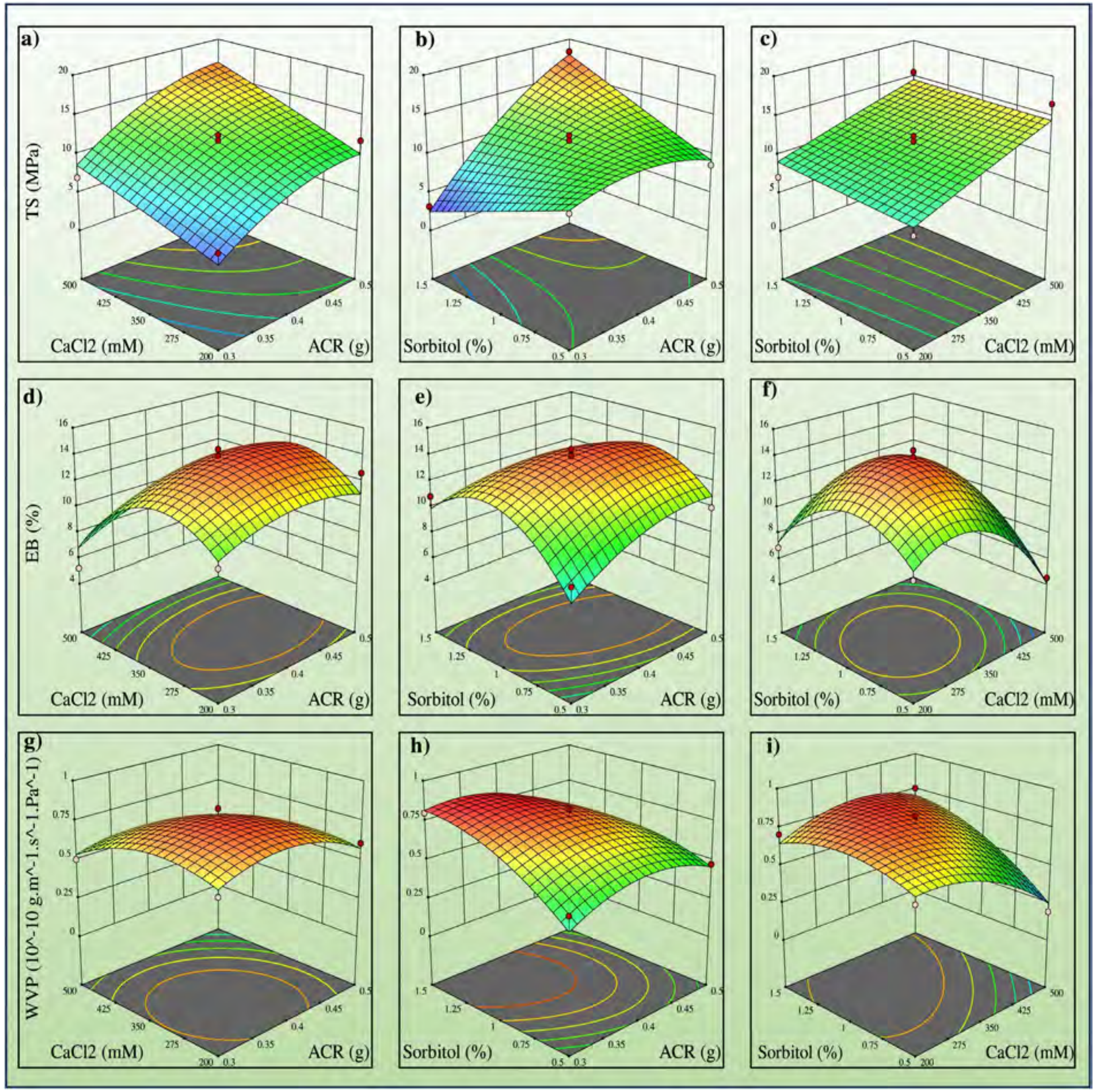
Cellulose

- Tensile strength:
  3.2-18.3 MPa
- Elongation at break:
  4.5-14.4%
- Water vapor permeability:
  $0.2\text{-}0.8 \times 10^{-10}$ $g.m^{-1}.s^{-1}.Pa^{-1}$

<u>Optimized condition</u>

- Alfalfa cellulose:
  0.5 g
- $CaCl_2$:
  461.3 mM
- Sorbitol:
  1.05%

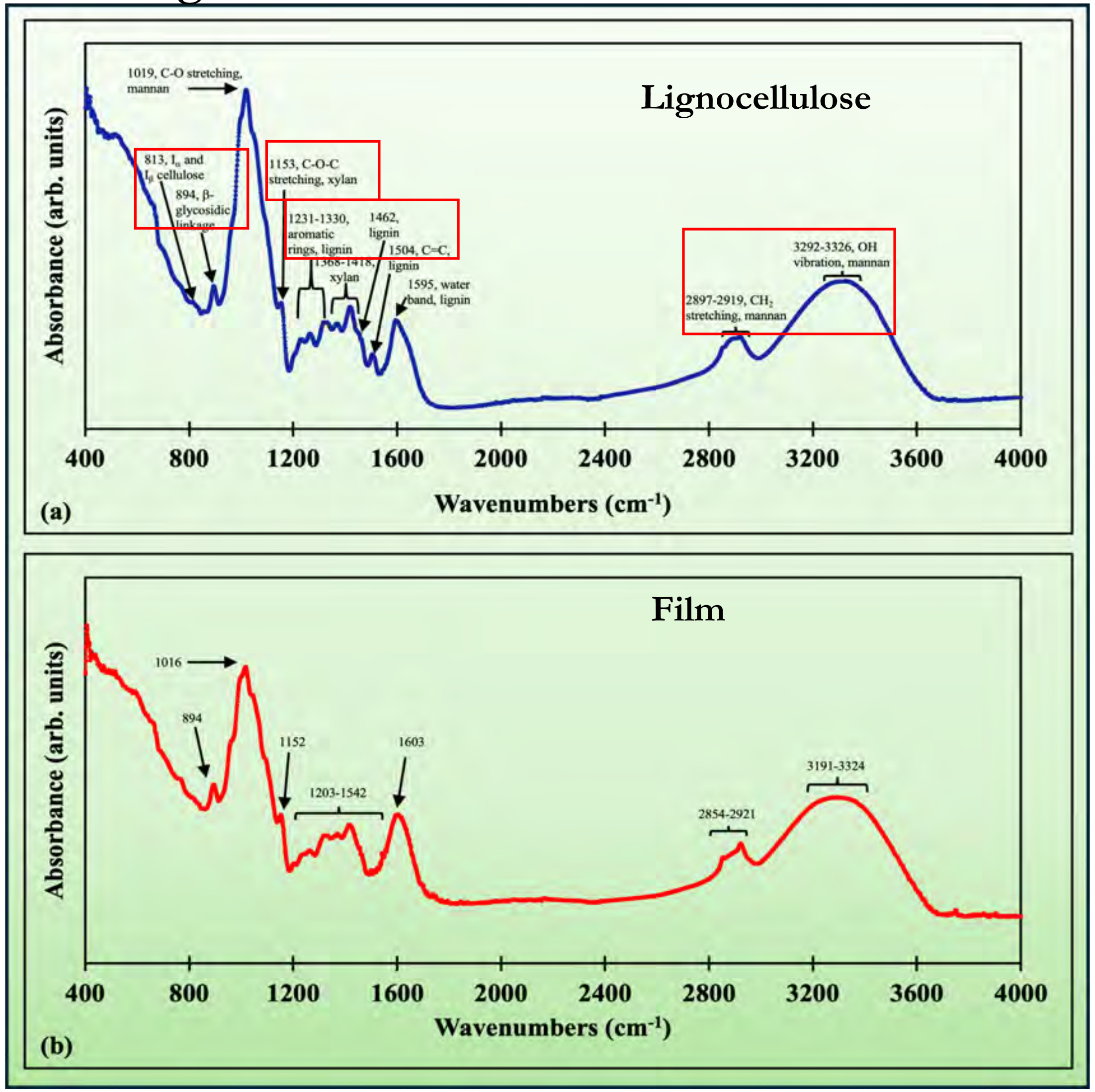
- Tensile strength:
  16.9 MPa
- Elongation at break:
  10.1%
- Water vapor permeability:
  0.47×10^{-10} $g.m^{-1}.s^{-1}.Pa^{-1}$



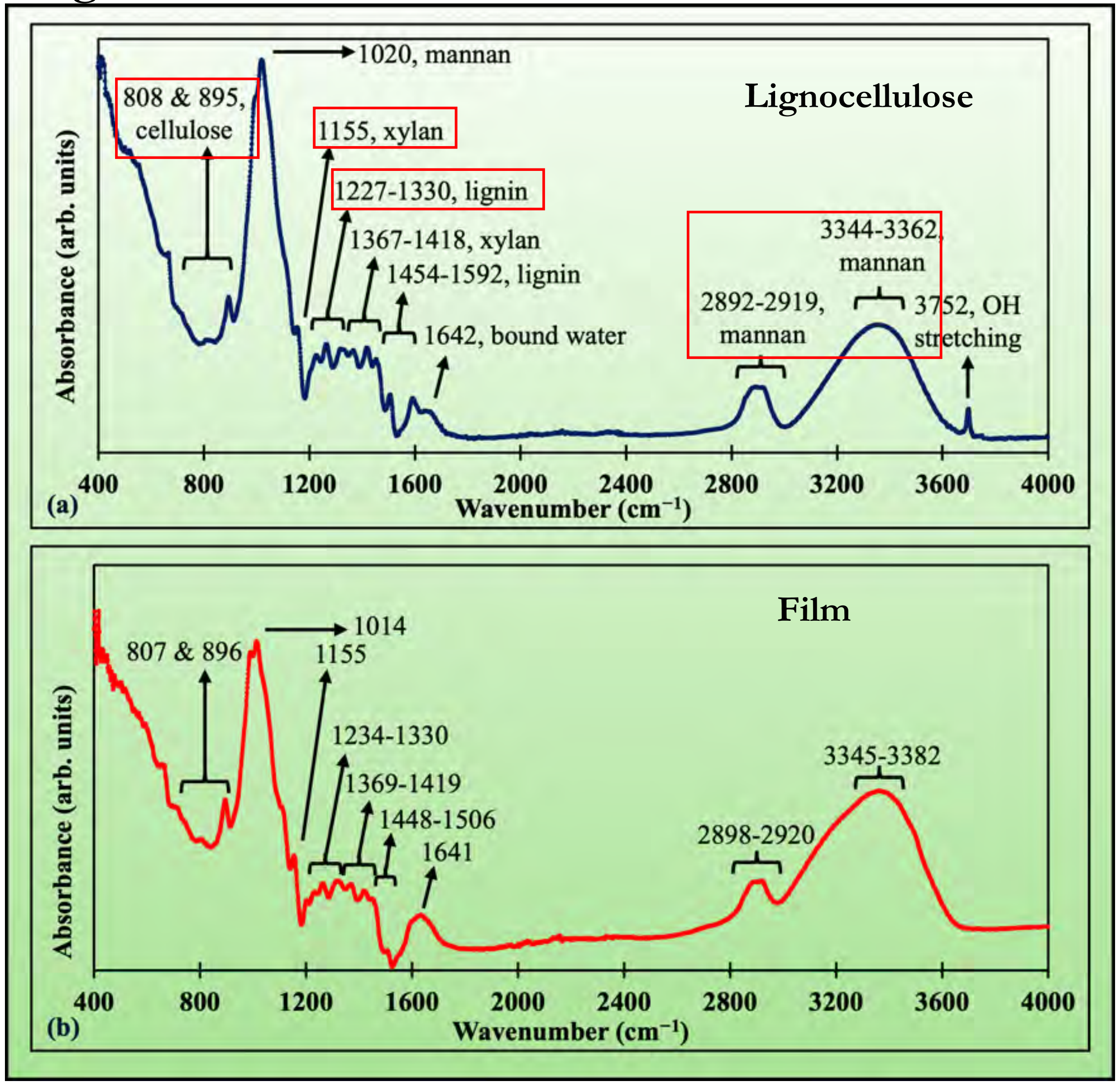
(Paudel & Janaswamy, 2025b)

FTIR

Lignocellulose film from 20% NaOH extract

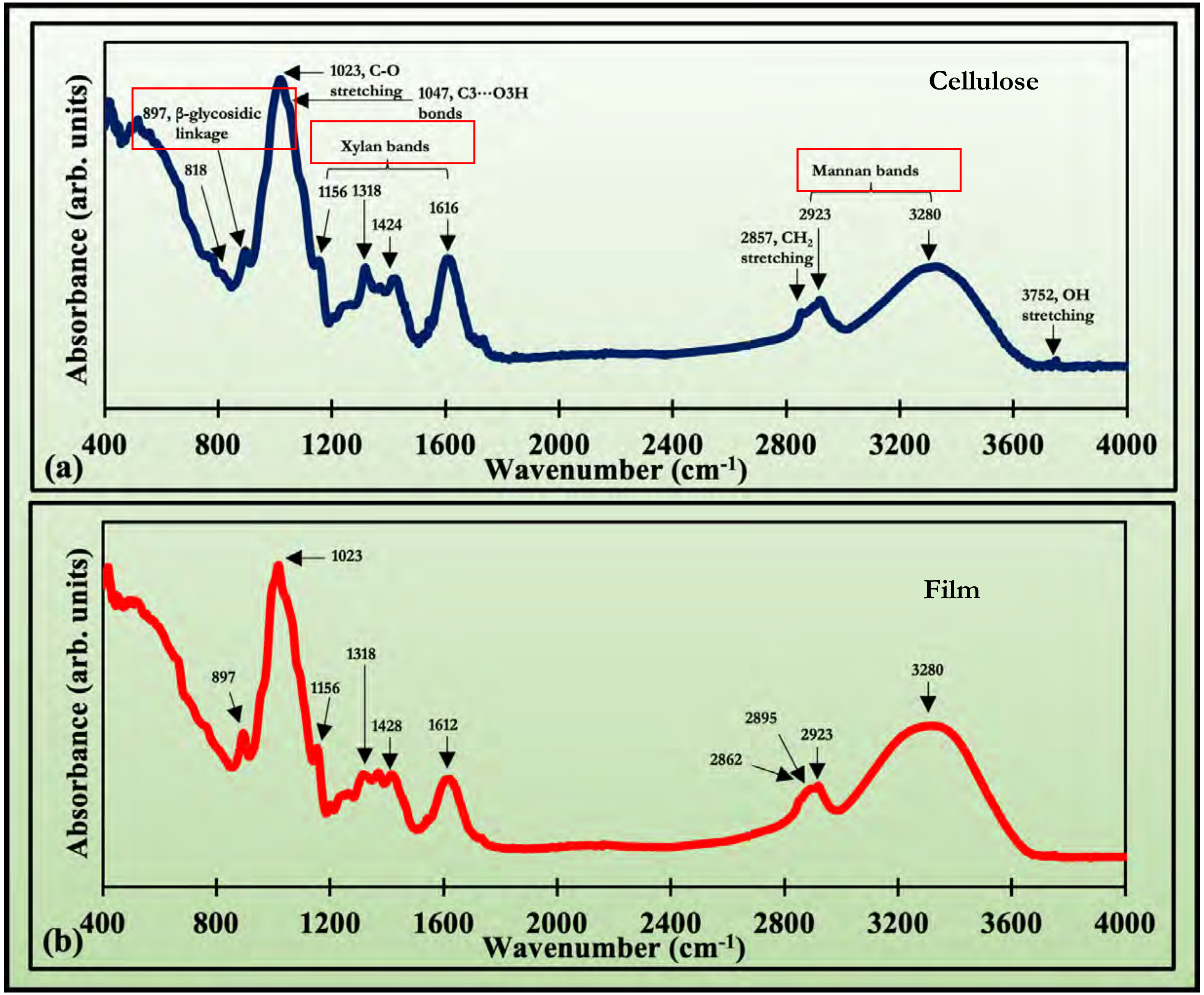


Lignocellulose film from 50% NaOH extract



(Paudel et al., 2026b, Paudel & Janaswamy, 2025a)

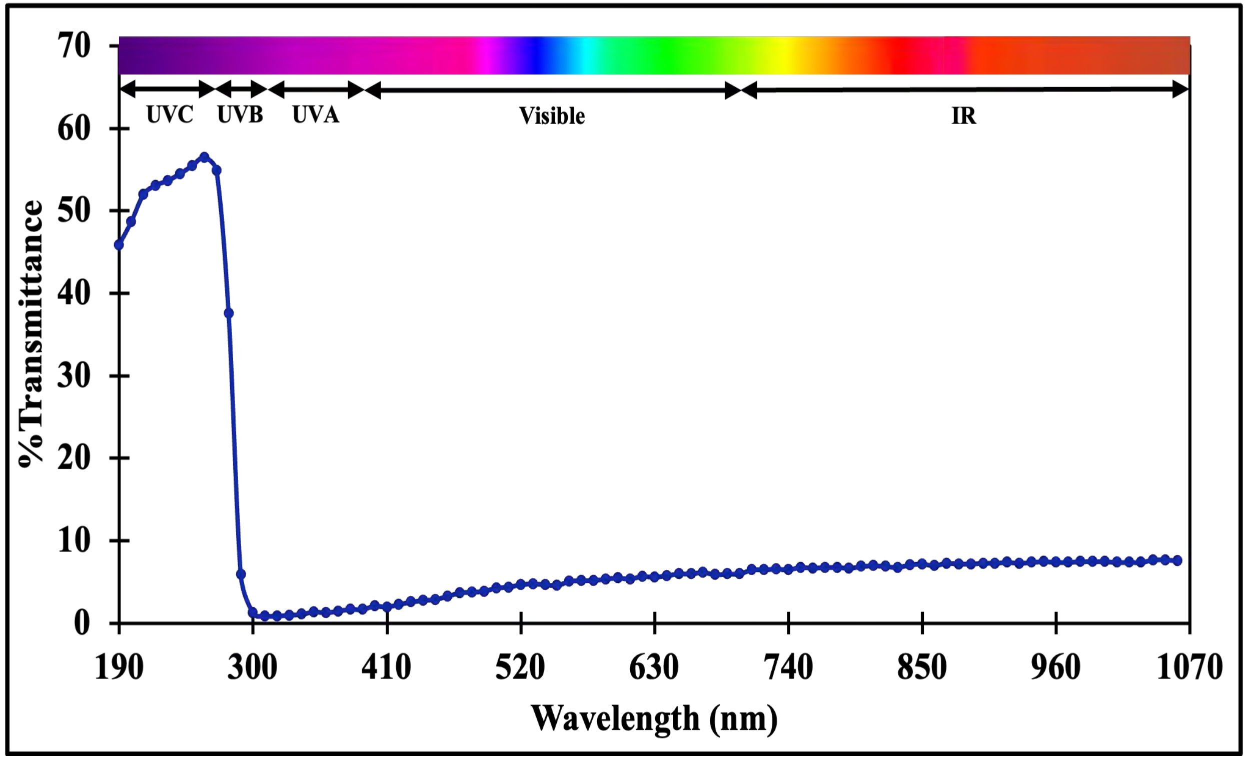
FTIR…



(Paudel & Janaswamy, 2025b)

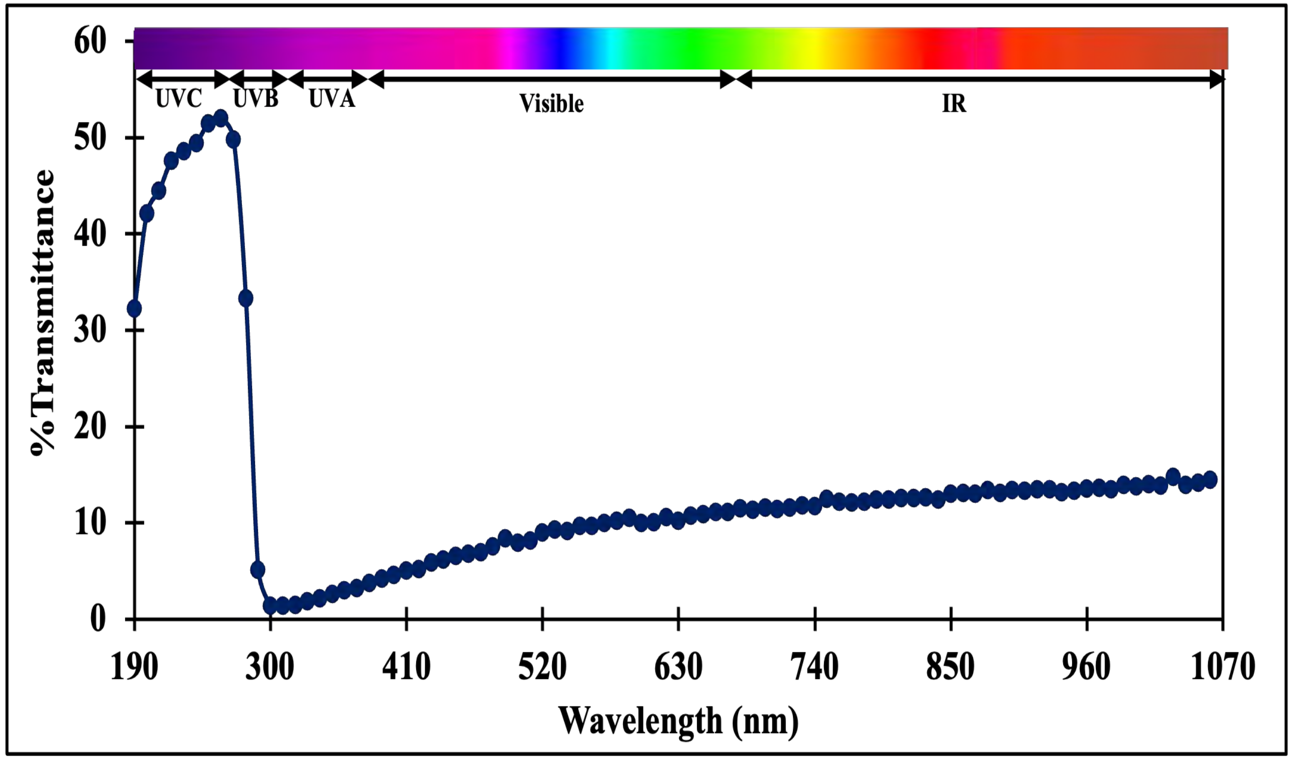
UV-VIS-IR LIGHT TRANSMITTANCE & ANTIOXIDANT ACTIVITY

Lignocellulose film from 20% NaOH extract



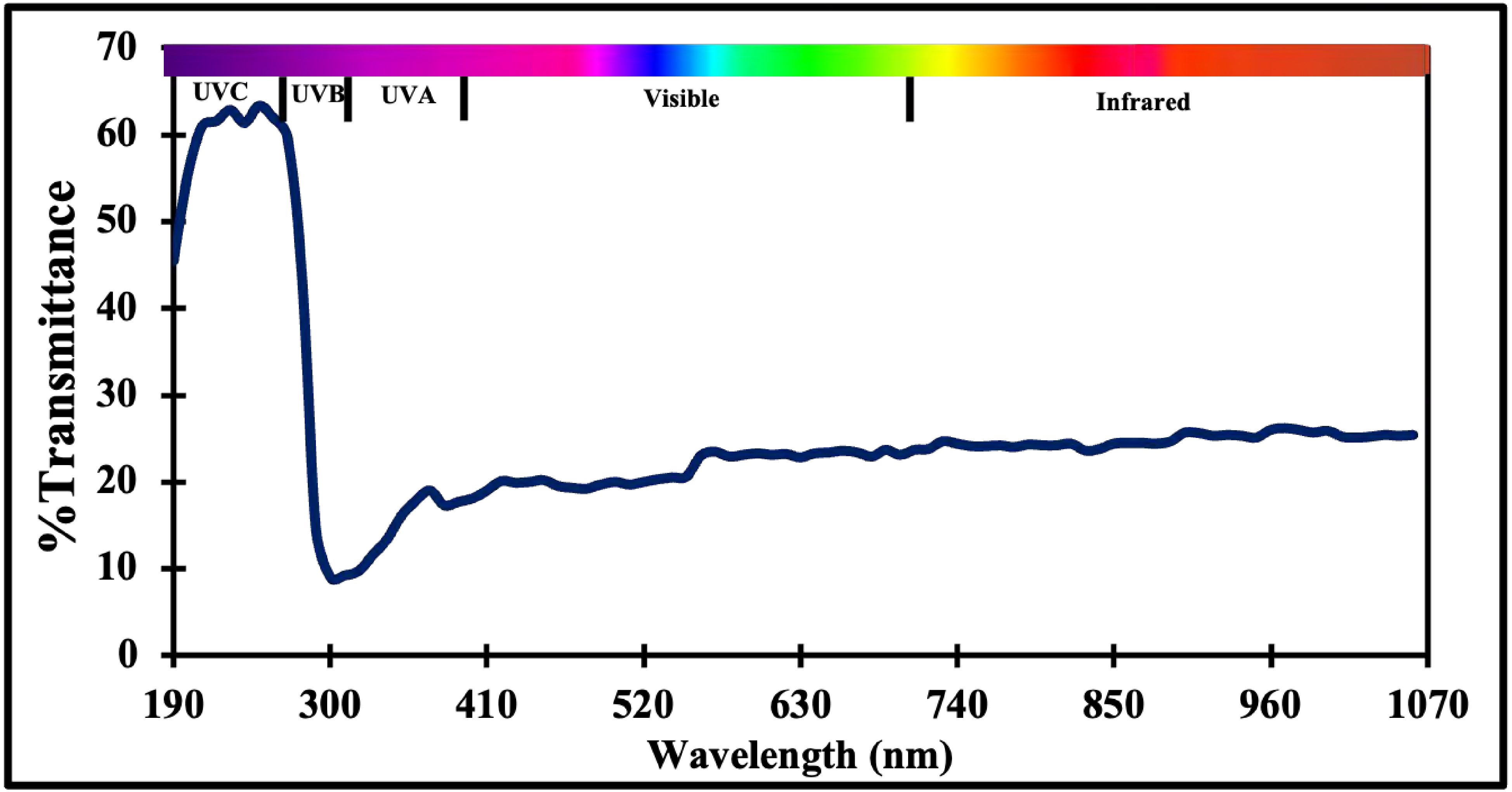
Antioxidant activity IC50 value
0.32±0.01 g/mL

Lignocellulose film from 50% NaOH extract



Antioxidant activity IC50 value
0.38±0.04 g/mL

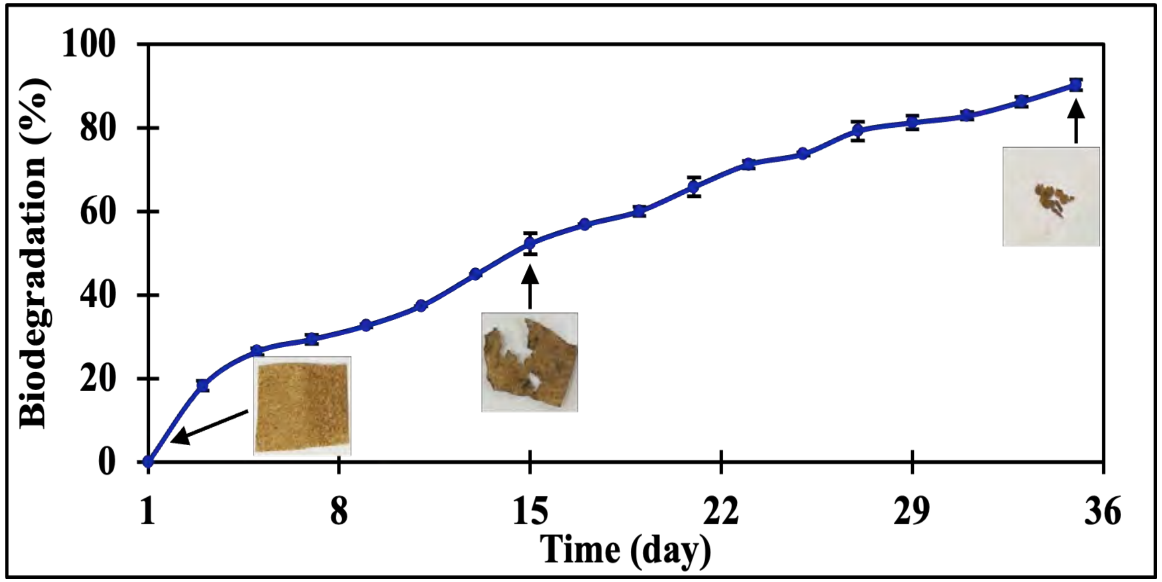
UV-VIS-IR LIGHT TRANSMITTANCE & ANTIOXIDANT PROPERTIES…



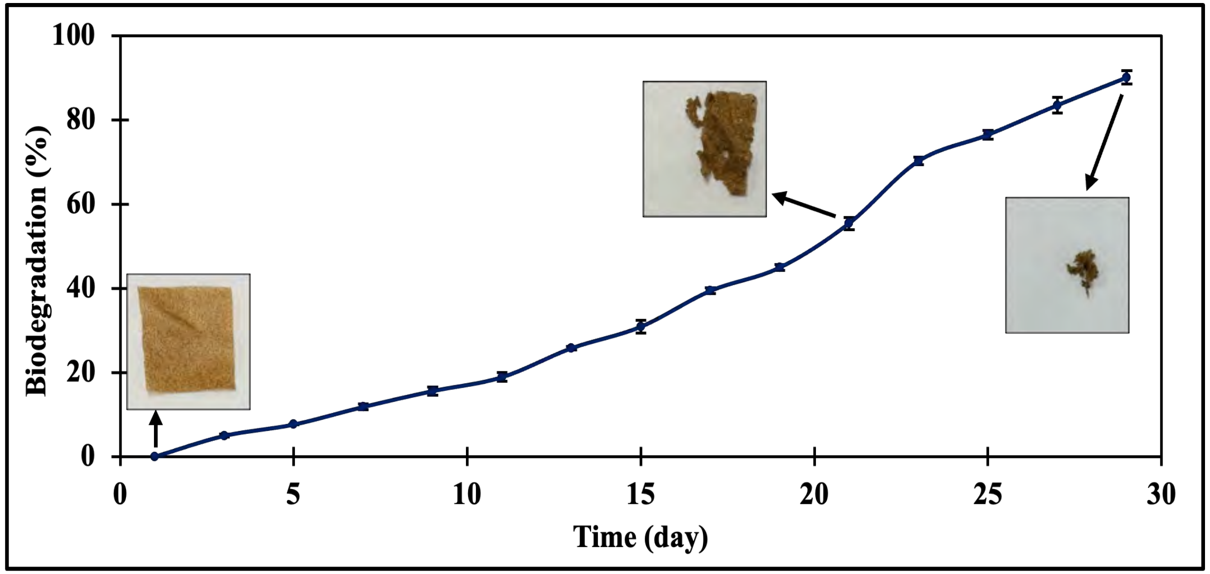
Likewise, the antioxidant activity IC50 value was: 0.41±0.01 g/mL

FILM BIODEGRADATION

Lignocellulose film from 20% NaOH extract

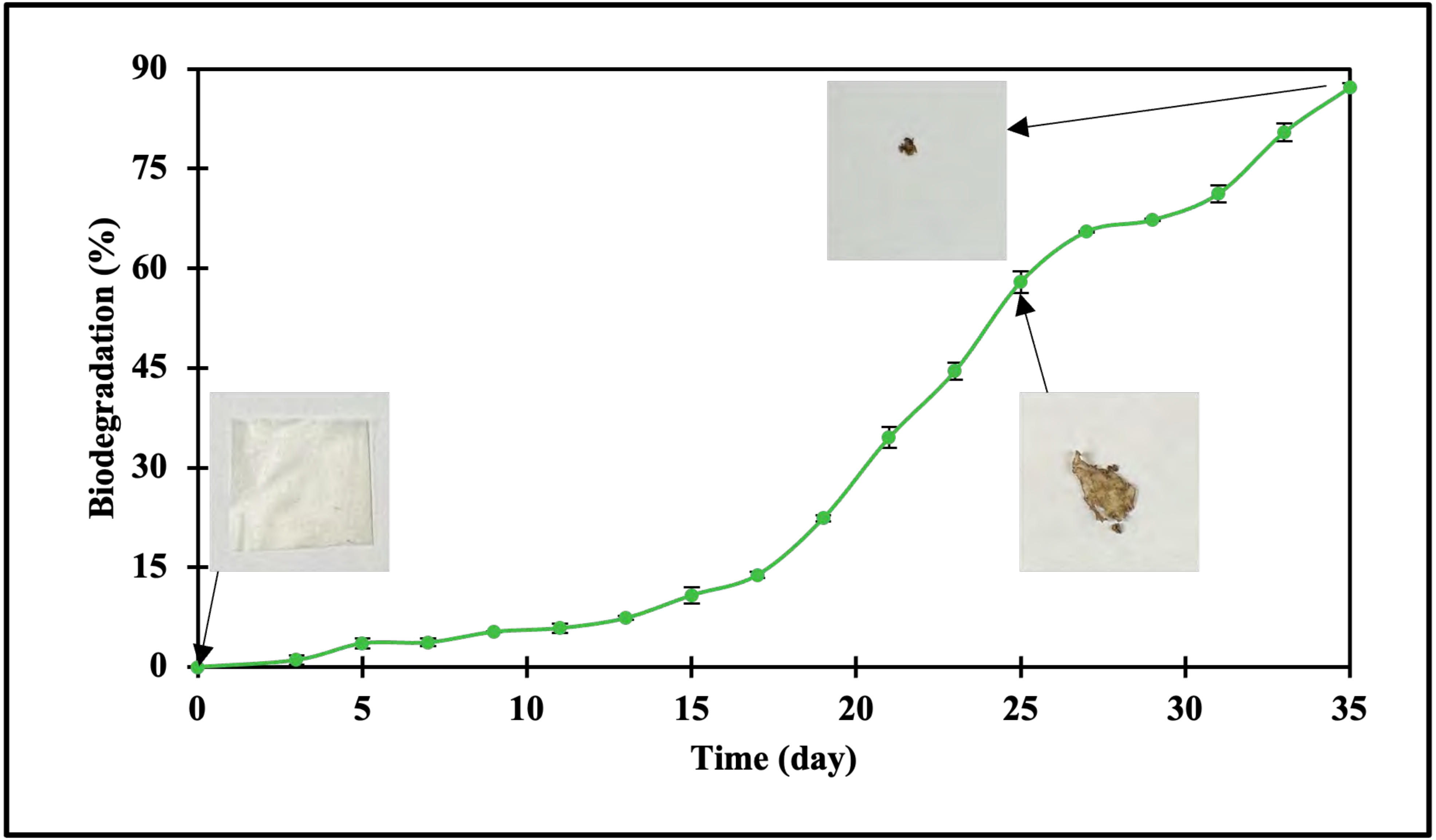


Lignocellulose film from 50% NaOH extract

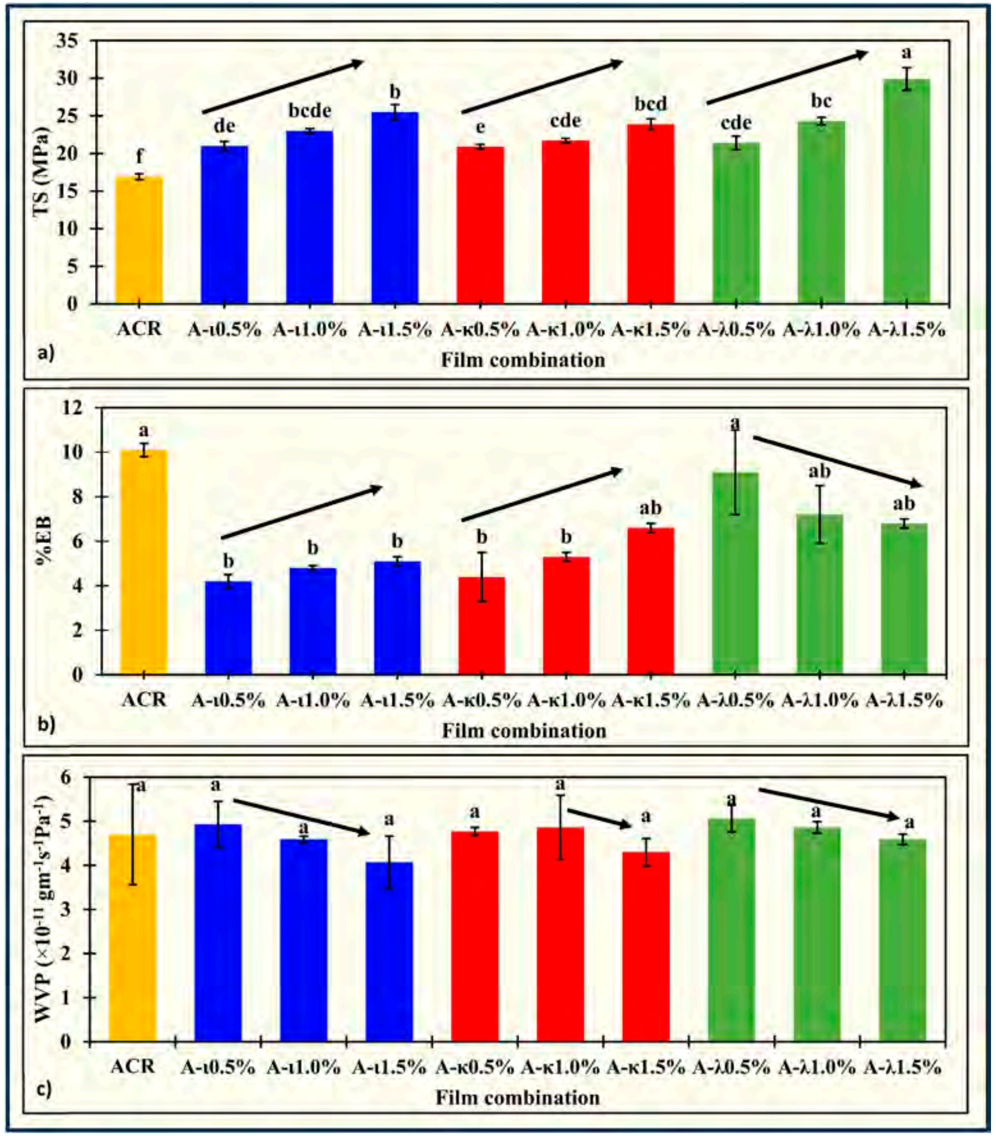


(Paudel et al., 2026b, Paudel & Janaswamy, 2025a)

FILM BIODEGRADATION…

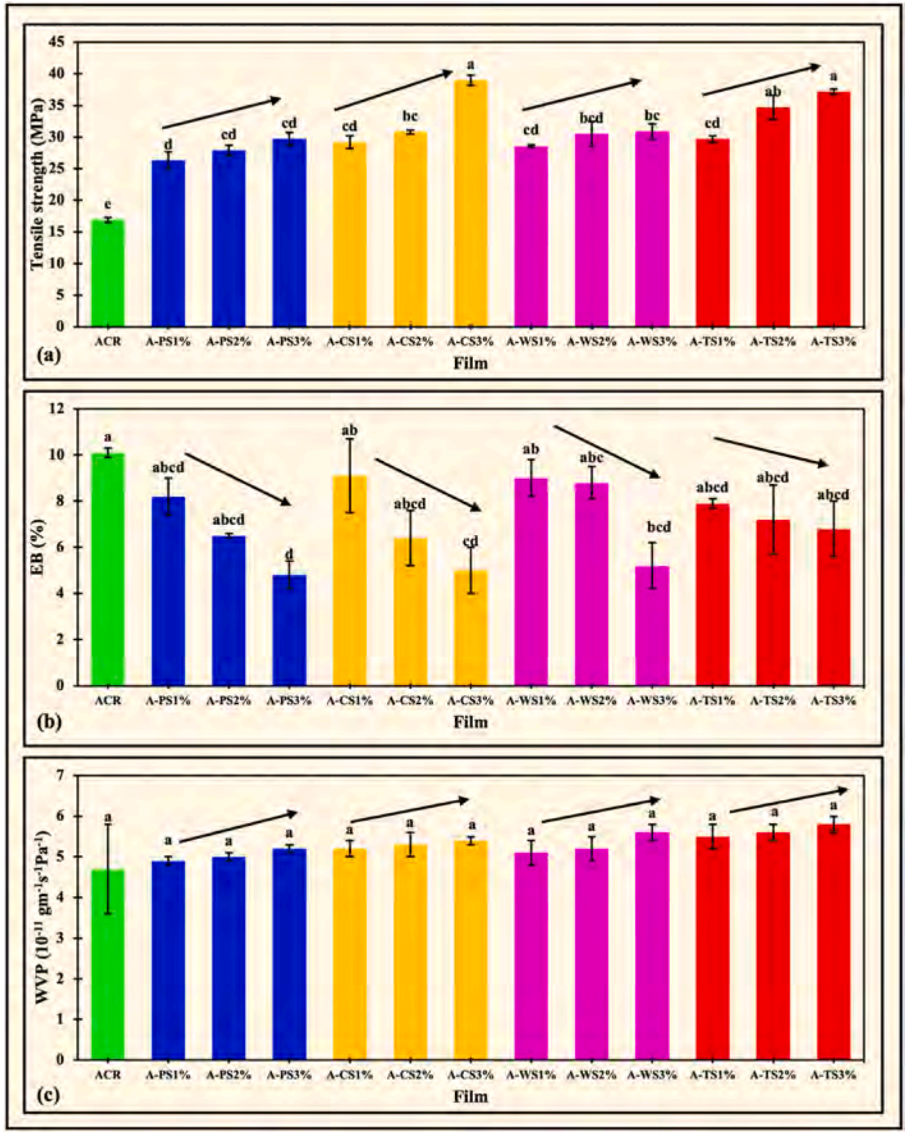


CELLULOSE-CARRAGEENAN & CELLULOSE-STARCH FILM



ι, κ, and λ: iota, kappa, and lambda carrageenan

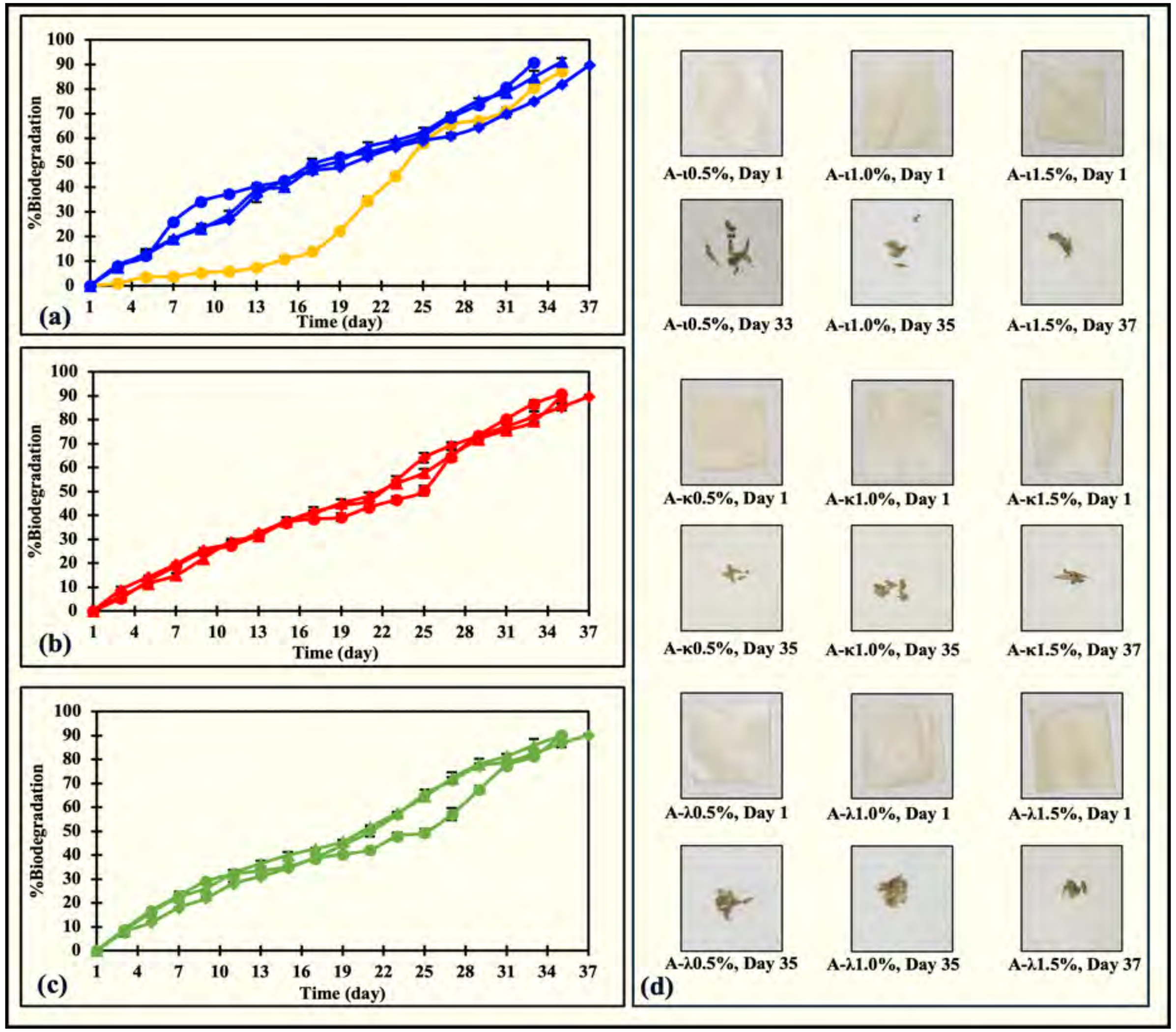
ACR: Alfalfa Cellulosic residue



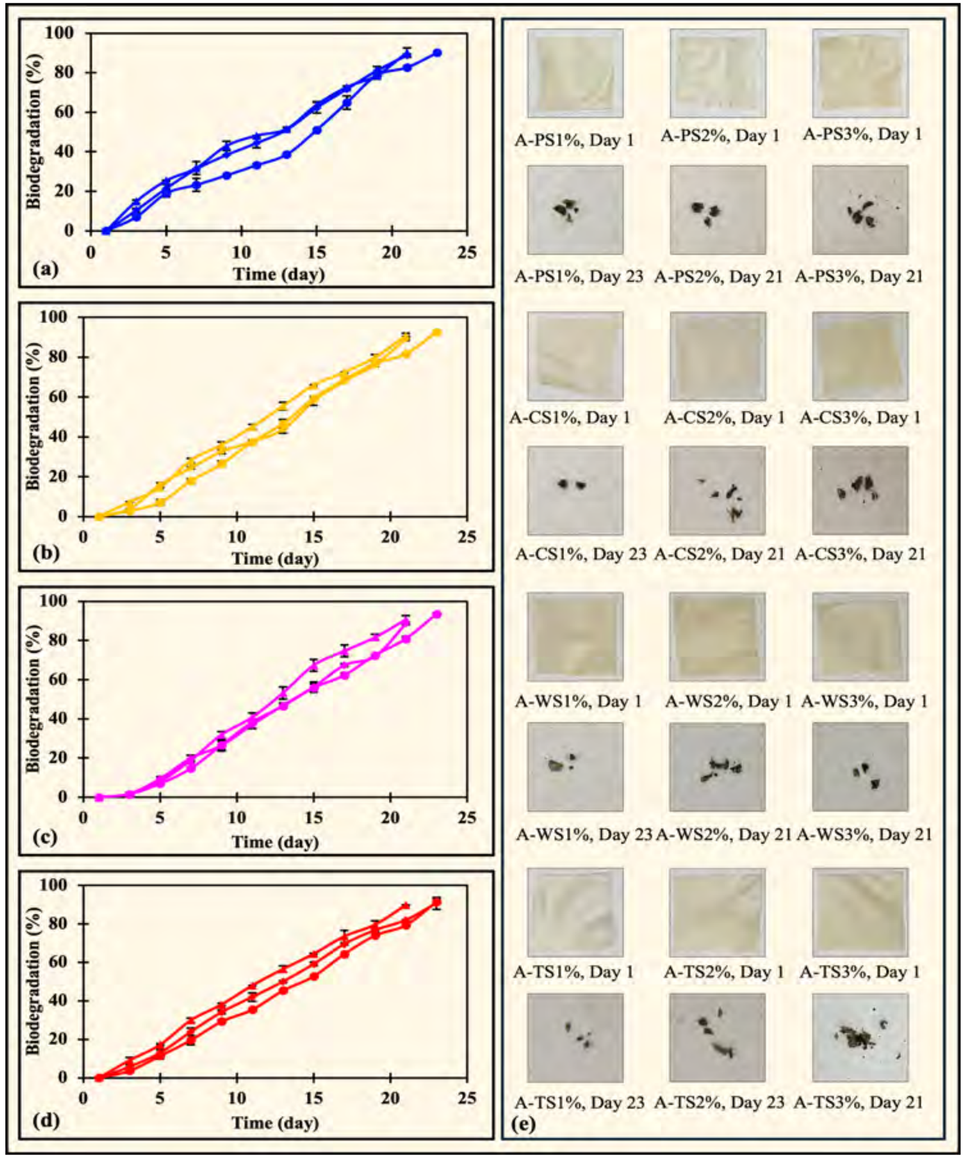
PS, CS, WS, and TS: Potato, Corn, Wheat, and Tapioca starches

(Paudel & Janaswamy, 2026a&b)

FILM BIODEGRADATION

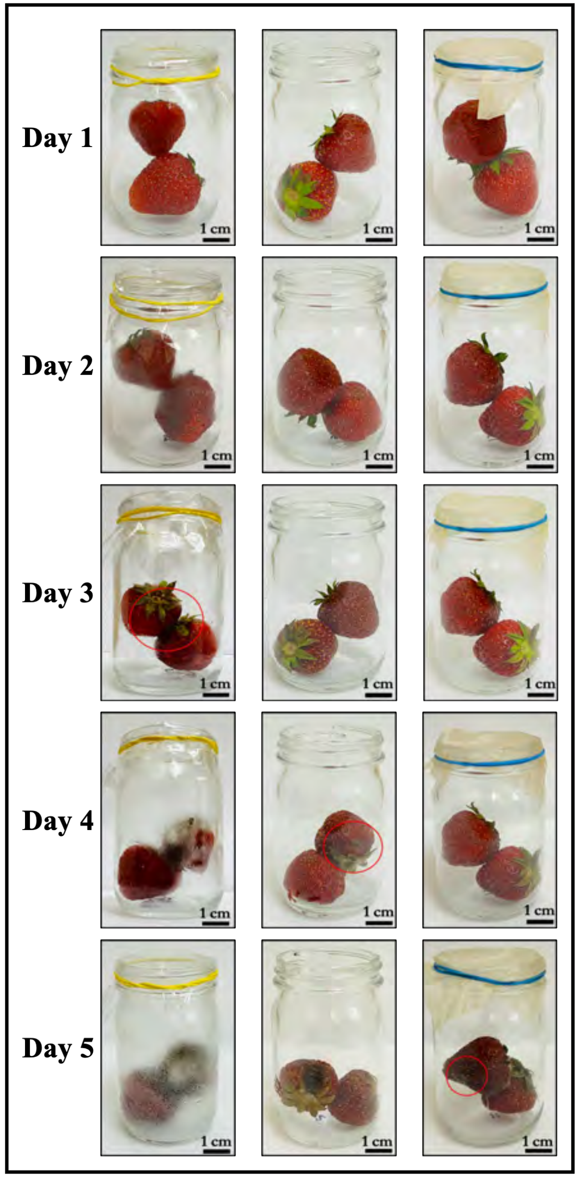


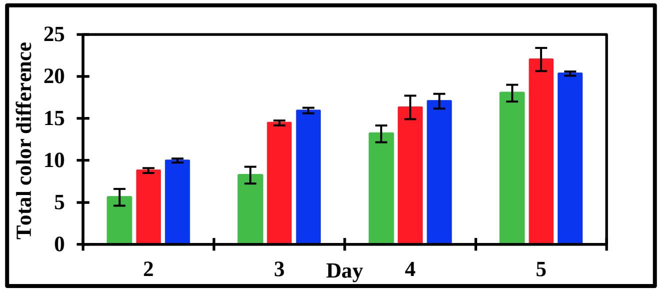
(a) ACR (yellow line) and ACR-ι-carrageenan (blue lines), (b) ACR-κ-carrageenan, and (c) ACR-λ-carrageenan films' biodegradation trend. (d) Films before and after biodegradation.

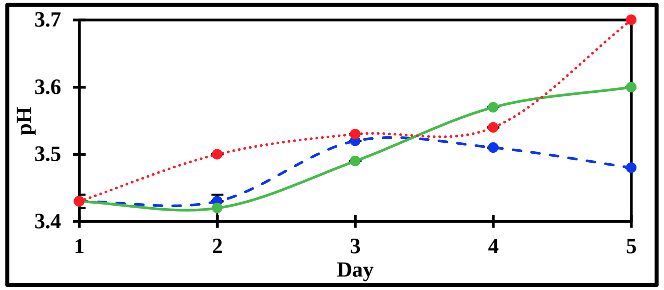


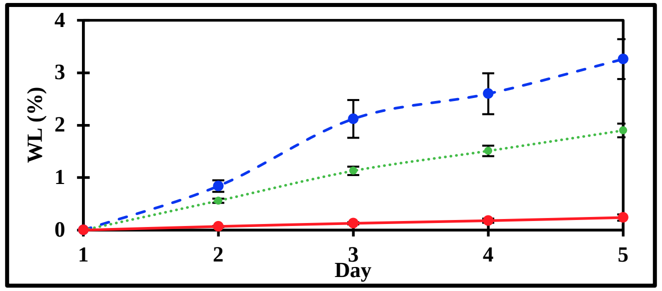
(a) ACR-Potato starch, (b) ACR-Corn starch, (c) ACR-Wheat starch, and (d) ACR-Tapioca starch films' biodegradation trends. (e) Films before and after biodegradation.

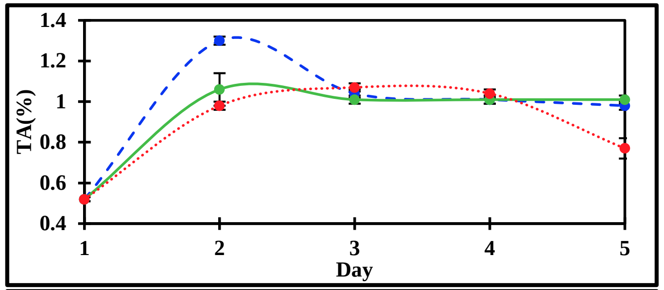
FRUIT STABILITY

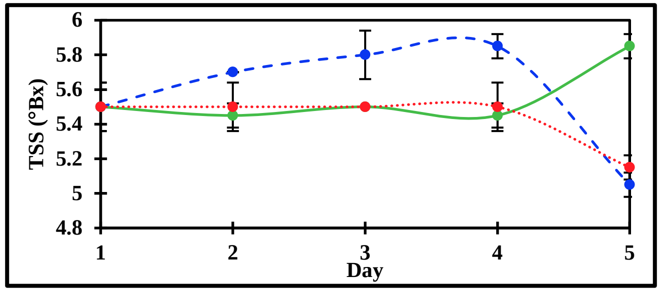


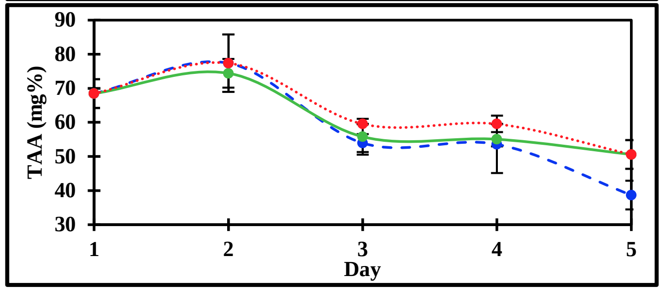


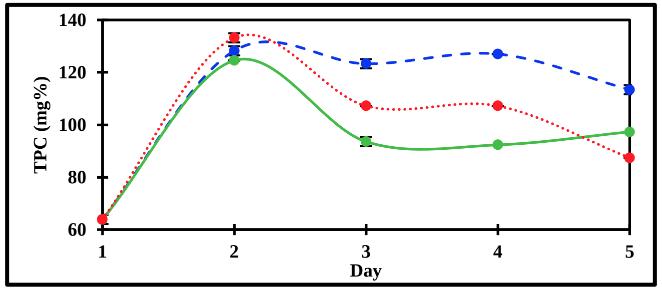












PS film-covered, uncovered, and ACR film-covered strawberries are denoted by red, blue, and green lines, respectively

CONCLUSIONS

- Alfalfa field residue demonstrates itself as a promising resource for producing biodegradable packaging films
- The lignocellulosic residue films had excellent light-blocking ability throughout the UV-Vis-IR region and had higher antioxidant activity
- The film tensile strength can be achieved up to 39 MPa
- Alfalfa cellulosic residue film extends strawberries' shelf life by two additional days compared to plastic films
- This research shows new opportunities for improving sustainable food packaging by bringing together material science, food technology, and environmental science. It demonstrates viable routes for creating biodegradable packaging materials derived from natural resources, reinforcing key principles of sustainability, circular bioeconomy, and reduced carbon footprint

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Sandeep Paudel | Sumi Regmi | Srinivas Janaswamy

International Journal of Biological Macromolecules 360 (2026) 151954

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Sandeep Paudel and Srinivas Janaswamy *

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Sandeep Paudel, Srinivas Janaswamy *

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Biodegradable films based on alfalfa cellulosic residue and carrageenan blends for sustainable food packaging

Sandeep Paudel and Srinivas Janaswamy *

In review: Carotenoid-Producing Yeast Reinforced Biodegradable Alfalfa Cellulose Films for Active Food Packaging and Raspberry Preservation, *Discover Foods.*

NEWS RELEASES

1. Impact of NIFA-funded research and outreach: Extending the shelf life of fruits. March 05, 2025. https://content.govdelivery.com/accounts/USDANIFA/bulletins/3d561b4
2. Biodegradable packaging from agricultural residues extends berry shelf life. February 18, 2025. https://www.packnode.org/en/sustainability/biodegradable-packaging-agricultural-residues-berries
3. Biodegradable packaging from agricultural residues extends shelf life of berries. February 14, 2025. https://www.hortidaily.com/article/9704784/biodegradable-packaging-from-agricultural-residues-extends-shelf-life-of-berries/
4. Biodegradable packaging made from agricultural residues prolongs the shelf life of berries. February 12, 2025. https://www.fresh-market.info/fruitsandvegetables/fruits/blueberries/biodegradable-packaging-made-from-agricultural-residues-prolongs-the-shelf-life-of-berrie
5. Biodegradable packaging from agricultural residues extends shelf life of berries. February 12, 2025. https://www.freshplaza.com/europe/article/9704131/biodegradable-packaging-from-agricultural-residues-extends-shelf-life-of-berries/
6. Eco-friendly films keep berries fresh longer. February 10, 2025. https://www.smallfarmcanada.ca/news/eco-friendly-films-keep-berries-fresh-longer/
7. Research at South Dakota State aims to extend shelf life of fruits. February 11, 2025. https://brookingsregister.com/stories/research-at-south-dakota-state-aims-to-extend-shelf-life-of-fruits,120994
8. Plant-based films boost fruit shelf life. February 06, 2025. https://southdakotaagconnection.com/news/plant-based-films-boost-fruit-shelf-life
9. Extending the shelf life of fruits. February 04, 2025. https://www.sdstate.edu/news/2025/02/extending-shelf-life-fruits

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