Chapter 16
Green Composite Film Synthesized from Agricultural Waste for Packaging Applications

Shobhit Dixit and Vijay Laxmi Yadav

1 Introduction

The extensive uses of non-biodegradable plastics have crossed the permissible limits of plastics wastes and created environment imbalance condition all over the world. The incinerated or land filled plenty available agro-wastes released greenhouse gases, smoke and particulate matters directly in to the environment and breached environment laws. So, researchers should find the appropriate way in order to reduce the plastics wastes generation by using alternate biodegradable material such as agricultural wastes, i.e., wheat straw, rice straw, hemp, kenaf, jute, sisal, etc. [1–4]. The cellulosic property of agro-waste has motivated the researchers to synthesize biodegradable composites due to their renewable properties, provided remarkable mechanical and thermal stabilities as compared to non-biodegradable plastics. Generally, polymers such as polyethylene, polylactic acid, polypropylene, starch and agro-wastes have remarkable stability for green packaging applications. The present chapter explores the reliable use of abundantly available biodegradable agricultural wastes for packaging applications such as food, sprout and active packaging's. The perfect use of agricultural wastes as a reinforcing agent in polymer matrix is the eye opener for current researchers. Many researchers promoted the use of agro-waste to synthesize biodegradable packaging film due to their cheap, lightweight, high tensile strength and benchmark thermal stability. Enhanced cellulose percentage area in agro-waste encourages suitability of this fiber to minimize the contribution of polymers with green agro-waste. Thus, the suitable use of agro-waste to synthesize green composites for packaging application is need of the hour [5, 6].

S. Dixit · V. L. Yadav (✉)
Department of Chemical Engineering and Technology, IIT BHU, Varanasi, Uttar Pradesh 221005, India
e-mail: vlyadav.che@itbhu.ac.in

S. Thomas and P. Balakrishnan (eds.), *Green Composites*,
Materials Horizons: From Nature to Nanomaterials,
https://doi.org/10.1007/978-981-15-9643-8_16

Native-agro-waste incorporated polymeric films have low mechanical and impact strengths as compared to petroleum-derived materials due to their hydrophilic nature. Inherent composition (lignin and hemicellulose) does not permit agro-waste to reinforce the polymeric film successfully. This behavior of agro-waste showed incompatibility found between the materials resulting in low desirable properties present in synthesized film. Moreover, this signified the less mechanical stability of the agro-waste reinforced polymeric film. However, many chemical modification techniques have enhanced surface property of agro-waste for appropriate blending in polymer matrix. This strategy helped to remove undesirable contents from agro-waste and created some void openings at the surface for improving blending characteristics. Chemical, physical and biological treatments are some of the frequently used popular techniques for reducing recalcitrance nature of agro-waste. The findings of many scientists elucidated that the mechanical and thermal characteristics of modified agro-waste incorporated polymeric film had considerably higher as compared to native-agro-waste reinforced polymeric film [7]. So the surface advancement in agro-waste is an emerging field in the polymeric composite research (Fig. 1). The prepared composite film is reliable as compared to synthetic packaging film in terms of contact angle, water vapor migration rate, flexural strength, water vapor permeability, mechanical stability and impact strength for green composite packaging application.

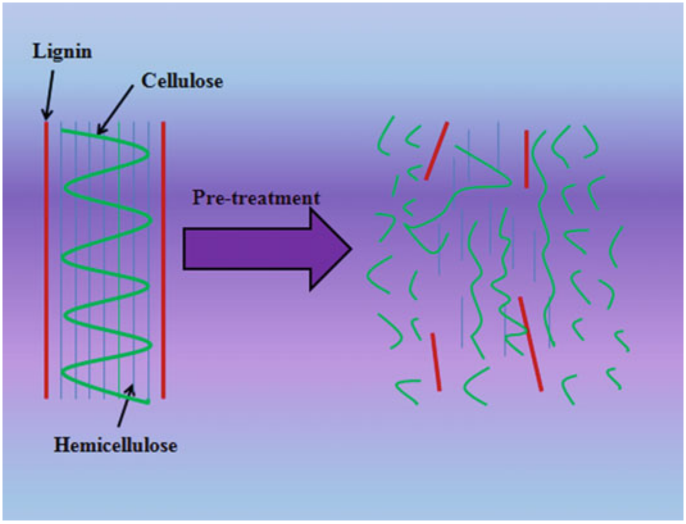

Fig. 1 Pretreatment of agricultural waste (*Source* Author)

1.1 Agro-waste

Agricultural wastes are generally produced from various from agricultural activities by the farmers. Agro-waste is waste which has no economic value. In India, the annual production of agro-waste is around 910 metric tons. Moreover, agro-waste has lightweight, readily available, comparatively low cost product and simple to process material. So, the safe disposal and better utilization of agro-waste are the key prospects for green life. Many scientists claimed that agro-waste had a property to use as filler in polymer matrix to increase composites tensile stability for various applications such as automotive, packaging, household and building industries [8]. Thus, it will build a new green environment for human life.

1.2 Classification of Agricultural Waste

In present juncture, the environment aspects encouraged researchers to increase the use of agro-waste as reinforcing agent in polymer matrix and maintain the environment balance condition. Agro-waste can be categorized in two ways, i.e., field residues and process residues (Fig. 2). Field residue is classified such as stems, stalks, leaves and seed pods and process residues are classified such as husks, seeds, roots and bagasse. [9]. Agro-wastes embedded products are required low maintenance with long life durable ability. However, these virtues are attracted industrialist to surging use of agro-waste for green composite preparation.

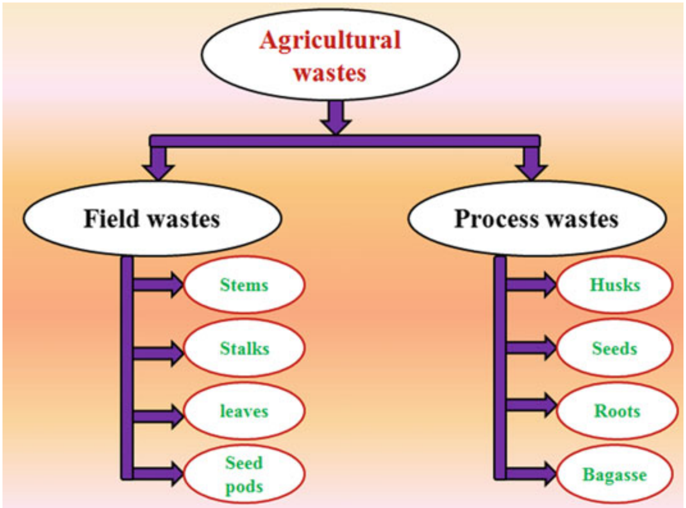

Fig. 2 Classification of agricultural wastes (*Source* Author)

1.3 *Chemical Composition of Agricultural Waste*

Agro-waste is composed of cellulose tightly embedded with hemicellulose protected by a strong wall of lignin. The percentage of cellulose, lignin and hemicellulose in agro-waste is varying with the type of agro-waste [9]. In order to attain the desirable properties, the higher cellulosic percentage in agro-waste has provoked researchers to use them for synthesizing green packaging film. The chemical composition of different types of agro-waste is depicted in Table 1.

2 Green Packaging Film Synthesized from Agricultural Waste

The required combination of agro-waste and polymers, i.e., green composites sustained a promising alternative to replace the non-biodegradable petroleum-derived materials for packaging applications. The main key factor is reduced the consumption of synthetic plastics, while researchers are moving toward renewable sources that are agricultural wastes to synthesize green plastics [4]. Recently, polymers are used for several applications like packaging, automotive and furniture goods. Thus, the use of agricultural wastes opens the way for biodegradable composite film and prepares a more sustainable waste-based packaging film that also helps to boost our economic sector. The various polymers such as polyethylene, polypropylene, polylactic acid

Table 1 Chemical composition of several types of agricultural waste

Agro-waste	Cellulose (%)	Hemicellulose (%)	Lignin (%)	References
Wheat straw	38–45	15–31	12–20	[10]
Hemp	57–77	14–22.4	3.7–13	[10]
Banana	53.45	28.56	15.46	[11]
Coir	43.44	0.25	45.84	[11]
Jute	59–61	22.1	15.9	[11]
Seed flax	43–47	24–26	21–23	[10]
Sisal	65–68	10–22	9.9–14	[12]
Bagasse	40–55.2	25.3	16.8	[10]
Kenaf	72	20.3	9	[13]
Rice husk	35–45	19–25	20	[13]
Rice straw	41–57	33	8–19	[13]
Flax	62–72	18.6–20.6	2–5	[14]
Ramie	68–76	13–16	0.6–0.7	[13]
Bamboo	26–65	30	5–31	[14]

Source Author

and polyvinyl alcohol have been frequently used for the packaging sector. Moreover, many agricultural wastes, i.e., wheat straw, hemp fiber, rice straw, kenaf, banana, jute etc. have been used as a filler in polymer matrix due to their considerable mechanical strength [4]. Although, the use of biocomposites for packaging applications made from lignocellulosic fiber is the most adaptable technique for green market (Table 2).

3 Some Improving Interfacial Interaction Techniques for Polymer/Agro-waste Composites

Pretreatment is the imperative technique involved in the effective reinforcement of agricultural waste in the polymer matrix. Several strategies are available such as physical, chemical, biological and physiochemical treatments for enhancing the interfacial interaction between fiber and polymer [30]. In the present scenario, these strategies have been reported in many literatures to attain the higher mechanical and thermal characteristics of the agro-waste incorporated green composite film (Fig. 3). Moreover, literature confirmed that treated-agro-waste was a promising substitute of polymer to synthesize green composites for packaging applications and serve as a potential alternative of non-biodegradable petroleum-derived materials [31]. In other words, these interfacial interaction improving techniques are the possible solution of poor mechanical stability of native agricultural waste-based polymer composite film.

3.1 Physical Pretreatment

In order to change the specific surface area or degree of polymerization of agro-waste, many physical treatment processes such as grinding, milling and chipping machines are used. The main focus of using this treatment is to avoid the wastage of chemicals use for requiring changes in lignocellulosic biomass. This treatment has reduced the particle size that increases the bulk density of treated-agro-waste and makes it appropriate for blending in the polymer matrix. The main disadvantage of this treatment is required higher energy consumption to operate the process [32].

3.2 Chemical Pretreatment

This pretreatment involved the reaction changes in agricultural waste. This treatment is easily removed undesirable materials (hemicellulose and lignin) from agro-waste and increases its cellulose digestibility for polymer adhesion. Many chemicals such

Table 2 Green packaging films synthesized from agricultural waste

Raw materials (reference)	Parameters	Pre-treatment	Method
Polystyrene (PS) [15]	Wheat straw (WS) (0–20%)	Chemical pre-treatment	Solvent casting method
Polyethylene (PE), polypropylene (PP) [4]	Wheat straw (0–20%)	Alkali treatment	Solvent casting method
Starch, polyvinyl alcohol (PVA) [16]	Banana fiber (BF) (0–30%)	NaOH treatment	Solvent casting method
Polylactic acid (PLA) [17]	Kenaf (KF)	Silane, alkaline treatment	Melt blending method
Cinnamon essential oil (CE), Bisphenol-A-based benzoxazine (BOZ) [5]	Hemp fiber (HF) (6–24%)	NaOH treatment	Hydraulic hot-press
PLA [18]	Glycidyl methacrylate-grafted (GMA) (1%), tert-butyl perbenzoate (TBPB) (0.5%), hemp hurd (HH) (10–30%)		Extrusion and injection
High density polyethylene(HDPE) [19]	HF (10–30%), BF (10–40%), maleic anhydride modified high density polyethylene (MAPE) (0.8–1.2%)		Injection
PP [20]	HF (5–15%)	NaOH treatment	Hand lay-up

(continued)

Table 2 (continued)

Raw materials (reference)	Parameters	Pre-treatment	Method
Polyhydroxy butyrate (PHB) [21]	Almond shell, rice husk, seagrass (10–20%)	NaOH treatment	Melt blending
Polylactic acid (PLA) [22]	WS (0–30%)	Solid state shear milling process (SSSM)	Extrusion
Green epoxy [23]	Sisal	Mechanical pressing	Unidirectional single layer laminates
Polyvinyl alcohol [24]	Rice straw (RS) (1–3%)	NaOH treatment	Solvent casting method
Hydroxy propyl methyl cellulose [25]	Jute fiber (0–3%)		Solvent casting method
Starch [26]	Rice husk fiber (2–10%)	Sulphuric acid treatment	Solvent casting method
Polylactic acid (PLA), poly (butylene succinate) PBS [27]	Cellulose crystals (CNC) (extracted from Hemp fiber	Sulphuric acid treatment	Solvent casting method
Low density polyethylene (LDPE) [28]	Doum fiber (DF) (5–30%)	NaOH treatment	Extrusion
PP [29]	Alfa fiber (AF)	Chemical treatment	Hot-press

(continued)

Table 2 (continued)

Results				Applications
PS Tensile strength (TS) ≈ 3 MPa Elongation at break (EAB) ≈ 210%	**PS/20% WS** TS ≈ 2.3 MPa EAB ≈ 110%	**PS/20% Alkali treated-WS** TS ≈ 3.56 MPa EAB ≈ 140 %	**PS/20% Acid treated-WS** TS ≈ 3.14 MPa EAB ≈ 130%	Packaging
PE/PP TS ≈ 46.5 MPa EAB ≈ 122% Contact angle ≈ 121° WVTR ≈ 47.50 g m^{-2} day^{-1}	**PE/PP/30% Native-WS** TS ≈ 34 MPa EAB ≈ 116.20% Contact angle ≈ 92° WVTR ≈ 132 g m^{-2} day^{-1}		**PE/PP/30% Alkali treated-WS** TS ≈ 45.010 MPa EAB ≈ 119.98% Contact angle ≈ 117° WVTR ≈ 51.89 g m^{-2} day^{-1}	Packaging
PVA/Starch/BF TS ≈ 30.8 MPa	**PVA/Starch/20% Alkali treated-BF** TS ≈ 34.4 MPa		**PVA/Starch/20% Acid treated-BF** TS ≈ 19.2 MPa	Packaging
PLA TS ≈ 55 MPa Impact strength (IS) ≈ 38 J/m		**PLA/Alkali treated-KF** TS ≈ 8 MPa IS ≈ 70 J/m		Packaging
CE/BOZ TS ≈ 28.05 MPa Tensile modulus (TM) ≈ 1.60 GPa Strain ≈ 2.10% Water absorption (WAB) ≈ 0.75%		**CE/BOZ/Treated-HF (20%)** TS ≈ 55.74 MPa TM ≈ 3.47 GPa Strain ≈ 1.38% WAB ≈ 5%		Packaging

(continued)

Table 2 (continued)

Results				Applications
PLA TS ≈ 65 MPa EAB ≈ 104.5% Flexible strength (FS) ≈ 100 MPa	**PLA/30% HH** TS ≈ 45MPa EAB ≈ 102% FS ≈ 60 MPa		**GMA-g-PLA/30% HH** TS ≈ 50 MPa EAB ≈ 102.1% FS ≈ 80 MPa	Packaging and disposable goods
HDPE TS ≈ 20 MPa Strain ≈ 30%	**65% HDPE/30% BF/5% MAPE** TS ≈ 50 MPa Strain ≈ 7.25%	**65% HDPE/15% HF/15% BF/5% MAPE** TS ≈ 47.5 MPa Strain ≈ 7.5%	**65% HDPE/30% HF/5% MAPE** TS ≈ 37.5 MPa Strain ≈ 7.5%	Packaging
PP TS at 10 mm thickness ≈ 40 MPa Fracture toughness (FT) at 10 mm Thickness ≈ 4.2 MPa $m^{0.5}$	**95% PP/5% Alkali treated-HF** TS at 10 mm thickness ≈ 60 MPa FT at 10 mm thickness ≈ 4.3 MPa $m^{0.5}$		**85% PP/15% Alkali treated-HF** TS at 10 mm thickness ≈ 44 MPa FT at 10 mm thickness ≈ 3.95 MPa $m^{0.5}$	Automobiles, military, construction, packaging, aerospace, railway coach
PHB TS ≈ 40 MPa EAB ≈ 101.7% WVP ≈ (2.1) × 10^{-15} kg s^{-1} Pa^{-1} m^{-1}	**PHB/20 % Almond shell** TS ≈ 35 MPa EAB ≈ 101.25% WVP ≈ 5 × 10^{-15} kg s^{-1} Pa^{-1} m^{-1}	**PHB/20% Rice husk** TS ≈ 29 MPa EAB ≈ 101.12% WVP ≈ 8 × 10^{-15} kg s^{-1} Pa^{-1} m^{-1}	**PHB/20% Seagrass** TS ≈ 40 MPa EAB ≈ 100.75% WVP ≈ 1.75 × 10^{-15} kg s^{-1} Pa^{-1} m^{-1}	Packaging
PLA TS ≈ 70 MPa EAB ≈ 107%	**PLA/30% WS** TS ≈ 60 MPa EAB ≈ 103.85%		**PLA/30% WS (SSSM)** TS ≈ 68 MPa EAB ≈ 103.1%	Packaging

(continued)

Table 2 (continued)

Results				Applications
Epoxy/73% native-SF TS ≈ 320 MPa		**Epoxy/77% treated-SF** TS ≈ 410 MPa		Packaging
PVA TS ≈ 41 MPa Transparency ≈ (68–95)%		**PVA/NaOH treated-RS** TS ≈ 98 MPa Transparency ≈ (52–90)%		Packaging
Hydroxypropylmethyl cellulose film TS ≈ 41.56 MPa EAB ≈ 141% Transparency at 600 nm ≈ 89% WVTR ≈ 0.053 $g/cm^2/24$ h		**3% Jute fiber based hydroxypropylmethyl cellulose film** TS ≈ 57.86 MPa EAB ≈ 145% Transparency at 600 nm ≈ 78% WVTR ≈ 0.039 $g/cm^2/24$ h		Packaging
Starch TS ≈ 2.5 MPa Water uptake ≈ 250%		**Starch/10% cellulose nanocrystals** Tensile strength ≈ 3.4 MPa Water uptake ≈ 100%		Packaging
PLA WVP ≈ 0.071×10^{-11} g mm kPa^{-1} h^{-1} m^{-2} Transmittance at 450 nm ≈ 88.2%	**PLA/20% PBS** WVP ≈ 0.042×10^{-11} g mm kPa^{-1} h^{-1} m^{-2} Transmittance at 450 nm ≈ 86%		**PLA/20% PBS/3% CNC** WVP ≈ 0.042×10^{-11} g mm kPa^{-1} h^{-1} m^{-2} Transmittance at 450 nm ≈ 81%	Packaging
LDPE TS ≈ 12.75 MPa EAB ≈ 140%		**70% LDPE/30% TDF** TS ≈ 10 MPa EAB ≈ 40%		Packaging
PP Young modulus (YM) ≈ 700 MPa TS ≈ 35 MPa	**Raw-AF/PP** YM ≈ 1000 MPa TS ≈ 31 MPa	**Alkali treated-AF/PP** YM ≈ 1200 MPa TS ≈ 31 MPa	**Esterified-AF/PP** YM ≈ 1400 MPa TS ≈ 32 MPa	**Etherified-AF/PP** YM ≈ 900 MPa TS ≈ 32 MPa

Source Author

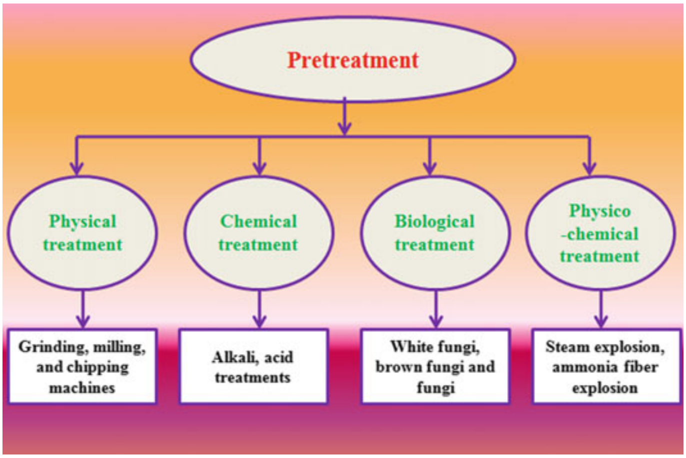

Fig. 3 Types of pretreatment (*Source* Author)

as alkalis (KOH, NaOH, $Ca(OH)_2$ etc.), acids (HCl, H_2SO_4, H_3PO_4, etc.) and ionic liquids have been commonly used for hydrolysis of hemicellulose with delignification process. This pretreatment can be considered in one of the most effective treatments for making more cellulose accessible [32].

3.3 Biological Pretreatment

Biological pretreatment is considered as a minimum energy required process in which agro-waste is kept under a control atmosphere with preferred microorganism. That microorganism has created the desirable surface changes of the agro-waste that makes biomass more acceptable for polymer adhesion. In this treatment, many organisms, i.e., white, brown and fungi have been used for enhancing the suitability of agro-waste in the polymer matrix. But this process has required larger residence time with an effective control atmosphere represent this treatment less attractive as compared to other pretreatment processes [33].

3.4 Physicochemical Pretreatment

This category of treatment is classified as a combination of physical and chemical changes. In this treatment, agro-waste is treated at higher temperatures and pressure which breaks the recalcitrance structure of agro-waste and creates some desirable surface changes in the agro-waste. Many physicochemical treatment processes are steam explosion, ammonia fiber explosion, liquid hot water hydrothermal treatment, wet oxidation, etc., are commonly used for improving interfacial interaction between polymer and agro-waste [32].

4 Various Testing Methods for Analyzing the Characteristics of Green Packaging Film

Several types of testing methods are used for analyzing the properties of agro-waste-based green composites for packaging application. Various testing methods such as water vapor transmission rate (WVTR), water vapor permeability (WVP), tensile test, optical characteristic test, impact test and contact angle have been used by researchers for analyzing the characteristics of packaging film [15].

4.1 Water Vapor Transmission Rate and Water Vapor Permeability

WVTR is an essential property for analyzing the quality of packaging film. This test explores the water vapor migration rate through the green composite film. A low value of this rate signifies synthesized film is applicable to keep warm products warm. In this test, a glass cup of 100 ml was taken and filled with distilled water. After that, cup is covered by synthesized film tightly and observed the weight of that wet cup chamber. This chamber is placed in an incubation chamber at a known temperature with fixed relative humidity. The changes in a total weight of wet cup chamber are analyzed at a regular interval of a time period. Water vapor transmission rate can be determined using the following equation.

$$\mathrm{WVTR} = \frac{\mathrm{WC}_1 - \mathrm{WC}_2}{\mathrm{WC}_1 * A * \mathrm{day}} \tag{1}$$

where WC_1 and WC_2 represent the initial and final weights of wet cup chamber; A represents the exposing area of wet cup chamber [34].

Water vapor permeability is also determined using the following equation.

$$\mathrm{WVP} = \frac{\mathrm{WVTR} * \text{thickness of green film}}{P(\mathrm{RH}_1 - \mathrm{RH}_2)} \tag{2}$$

where P is saturation vapor pressure at constant temperature, and RH_1 and RH_2 are relative humidity of inside and outside of the wet cup chamber.

4.2 Tensile Test

This test is demonstrated the mechanical stability of green composite film using universal testing machine. This property depends on materials thickness, testing speed and method of preparation. In this test, film is cut in strip form at fixed gauge length and gauge width according to ASTM. Generally, many researchers have been used ASTMD 0882 for materials thickness less than 1 mm. A sample is fixed between the grips of testing machine and allowed to elongate a material at a known testing speed. Further, the machine calculated the ultimate tensile strength and maximum flexibility of the green film that plays a vital role in observing the mechanical stability of the material [4].

4.3 Dart Impact Test

Dart impact strength is an important property for industries of packaging sectors to access the durability of the packaging film. A sample is cut in required dimensions according to ASTM. Commonly, ASTMD1709 has been used frequently for analyzing the impact strength of the green packaging film. In this impact test, a dart of known weight is free fell on the surface of the film at a fixed height and observed that film is punctured or not. If it is not punctured, again increase the weight of dart and repeated the process. The phenomena helped to understand the impact strength of the green packaging film. The energy required to fracture the surface of film is equivalent to drop a known dart impact failure weight at fixed height on the sample.

4.4 Contact Angle Test

In order to elucidate the hydrophobic property of green film, water contact angle is measured at vapor–liquid interface meets at solid surface of sample using drop shape analyzer machine. Sessile drop method is the simplest way to observe the water repelling quality of the prepared film. This test is measured by the wettability of the surface of the sample. In this test, a drop of distilled water is dropped on the surface of the composite film and examined the surface hydrophobicity of the sample. Higher contact angle (greater than 90°) signified the hydrophobic property of the green composite film [4].

4.5 Optical Characteristics Test

This test visualized the transparency of the green composite film for packaging applications using UV–Vis spectrophotometer machine. Green film is cut in strip form and placed in a cuvette using blank cuvette as a reference in the machine and scanned over the wavelength of 400–800 nm visible range. This test is provided the transparency of the sample over visible range and demonstrated the optical characteristics of the green film [35].

4.6 Thermal Stability Test

Thermal stability test is provided information about ability of the packaging film to resist the action of heat using PerkinElmer thermogravimetric analyzer. This test represents the maximum temperature at which our materials can sustain their mechanical property. In this test, a known weight of green film is placed in a machine and allowed to heat from 30 to 800 °C at required heating rate. This process is done in a nitrogen-controlled atmosphere for avoiding the undesirable thermal cracking of the green film. Thermal analyzer provided the graph between mass (%) with temperature. This graph helped to understand the main thermal degradation temperature range of the green composite film [21].

5 Conclusion

In summary, the effect of agricultural wastes on the packaging properties of the polymeric film was evaluated. This chapter has enlightened the perfect use of agricultural waste as a reinforcing agent in the polymer matrix for packaging applications. Various improving interfacial interaction techniques, i.e., physical, chemical, biological and physiochemical treatments have been discussed in order to enhance the suitability of agricultural waste in the polymer matrix in terms of water vapor migration rate, transparency, mechanical and thermal stabilities. Published literature confirmed the importance of various strategies for agricultural waste for polymer blending. This chapter is also explored the testing methods, i.e., water vapor transmission rate, water vapor permeability, contact angle, tensile test, impact test, optical characteristics test, thermal stability test and some ASTM standards for tensile and impact tests. This chapter described a brief introduction for the utilization of abundantly available agricultural wastes as filler in the polymer matrix for green packaging application.

References

1. Dixit S, Yadav VL (2019) Synthesis of green thermally resistant composite: a review. Indian J Chem Technol (IJCT) 26:494–503
2. Dixit S, Yadav VL (2020) Biodegradable polymer composite films for green packaging applications. In: Kharissova OV, Martínez LMT, Kharisov BI (eds) Handbook of nanomaterials and nanocomposites for energy and environmental applications. Springer International Publishing, Cham, pp 1–17
3. Dixit S, Joshi B, Kumar P, Yadav VL (2020) Novel hybrid structural biocomposites from alkali treated-date palm and coir fibers: morphology, thermal and mechanical properties. J Polym Environ
4. Dixit S, Yadav VL (2019) Optimization of polyethylene/polypropylene/alkali modified wheat straw composites for packaging application using RSM. J Cleaner Prod 240:118228
5. Zegaoui A, Derradji M, Ma R-K, Cai W-A, Medjahed A, Liu W-B, Dayo AQ, Wang J, Wang G-X (2018) Influence of fiber volume fractions on the performances of alkali modified hemp fibers reinforced cyanate ester/benzoxazine blend composites. Mater Chem Phys 213:146–156
6. Dayo AQ, Gao B-C, Wang J, Liu W-B, Derradji M, Shah AH, Babar AA (2017) Natural hemp fiber reinforced polybenzoxazine composites: curing behavior, mechanical and thermal properties. Compos Sci Technol 144:114–124
7. Dixit S, Yadav VL (2019) Comparative study of polystyrene/chemically modified wheat straw composite for green packaging application. Polym Bull 1–20
8. Chawla K, Bastos A (1979) The mechanical properties of jute fibers and polyester/jute composites. Mech Behav Mater 3:191–196
9. Sadh PK, Duhan S, Duhan JS (2018) Agro-industrial wastes and their utilization using solid state fermentation: a review. Bioresour Bioprocess 5:1
10. Chaitanya S, Singh AP, Singh I (2017) Natural fiber-reinforced biodegradable and bioresorbable polymer composites, p 163
11. Shahinur S, Hasan M (2019) Jute/Coir/Banana fiber reinforced bio-composites: critical review of design, fabrication, properties and applications. In: Reference module in materials science and materials engineering. Elsevier, Amsterdam
12. Senthilkumar K, Saba N, Rajini N, Chandrasekar M, Jawaid M, Siengchin S, Alotman OY (2018) Mechanical properties evaluation of sisal fibre reinforced polymer composites: a review. Constr Build Mater 174:713–729
13. Faruk O, Bledzki AK, Fink H-P, Sain M (2012) Biocomposites reinforced with natural fibers: 2000–2010. Prog Polym Sci 37:1552–1596
14. Santhosh Kumar S, Hiremath S (2019) Natural fiber reinforced composites in the context of biodegradability: a review. In: Reference module in materials science and materials engineering. Elsevier, Amsterdam
15. Dixit S, Yadav VL (2020) Comparative study of polystyrene/chemically modified wheat straw composite for green packaging application. Polym Bull 77:1307–1326
16. Srivastava KR, Singh MK, Mishra PK, Srivastava P (2019) Pretreatment of banana pseudostem fibre for green composite packaging film preparation with polyvinyl alcohol. J Polym Res 26:95
17. Islam MS, Rahman MM, Hasan M (2019) Kenaf fiber based bio-composites: processing, characterization and potential applications
18. Khan BA, Na H, Chevali V, Warner P, Zhu J, Wang H (2018) Glycidyl methacrylate-compatibilized poly (lactic acid)/hemp hurd biocomposites: processing, crystallization, and thermo-mechanical response. J Mater Sci Technol 34:387–397
19. Sarasini F, Tirillò J, Sergi C, Seghini MC, Cozzarini L, Graupner N (2018) Effect of basalt fibre hybridisation and sizing removal on mechanical and thermal properties of hemp fibre reinforced HDPE composites. Compos Struct 188:394–406
20. Madhusudhana H, Desai B, Venkatesha C (2018) Experimental investigation on parameter effects on fracture toughness of hemp fiber reinforced polymer composites. Mater Today Proc 5:20002–20012

21. Sánchez-Safont EL, Aldureid A, Lagarón JM, Gámez-Pérez J, Cabedo L (2018) Biocomposites of different lignocellulosic wastes for sustainable food packaging applications. Compos B Eng 145:215–225
22. Yang S, Bai S, Wang Q (2018) Sustainable packaging biocomposites from polylactic acid and wheat straw: enhanced physical performance by solid state shear milling process. Compos Sci Technol 158:34–42
23. Zuccarello B, Marannano G, Mancino A (2018) Optimal manufacturing and mechanical characterization of high performance biocomposites reinforced by sisal fibers. Compos Struct 194:575–583
24. Perumal AB, Sellamuthu PS, Nambiar RB, Sadiku ER (2018) Development of polyvinyl alcohol/chitosan bio-nanocomposite films reinforced with cellulose nanocrystals isolated from rice straw. Appl Surf Sci 449:591–602
25. Orasugh JT, Saha NR, Rana D, Sarkar G, Mollick MMR, Chattoapadhyay A, Mitra BC, Mondal D, Ghosh SK, Chattopadhyay D (2018) Jute cellulose nanofibrils/hydroxypropylmethylcellulose nanocomposite: a novel material with potential for application in packaging and transdermal drug delivery system. Ind Crops Prod 112:633–643
26. Kargarzadeh H, Johar N, Ahmad I (2017) Starch biocomposite film reinforced by multiscale rice husk fiber. Compos Sci Technol 151:147–155
27. Luzi F, Fortunati E, Jiménez A, Puglia D, Pezzolla D, Gigliotti G, Kenny JM, Chiralt A, Torre L (2016) Production and characterization of PLA_PBS biodegradable blends reinforced with cellulose nanocrystals extracted from hemp fibres. Ind Crops Prod 93:276–289
28. Arrakhiz FZ, El Achaby M, Malha M, Bensalah MO, Fassi-Fehri O, Bouhfid R, Benmoussa K, Qaiss A (2013) Mechanical and thermal properties of natural fibers reinforced polymer composites: doum/low density polyethylene. Mater Des 43:200–205
29. Arrakhiz F, Elachaby M, Bouhfid R, Vaudreuil S, Essassi M, Qaiss A (2012) Mechanical and thermal properties of polypropylene reinforced with Alfa fiber under different chemical treatment. Mater Des 35:318–322
30. Agbor VB, Cicek N, Sparling R, Berlin A, Levin DB (2011) Biomass pretreatment: fundamentals toward application. Biotechnol Adv 29:675–685
31. Dhakal HN, Sarasini F, Santulli C, Tirillò J, Zhang Z, Arumugam V (2015) Effect of basalt fibre hybridisation on post-impact mechanical behaviour of hemp fibre reinforced composites. Compos A Appl Sci Manuf 75:54–67
32. Jędrzejczyk M, Soszka E, Czapnik M, Ruppert AM, Grams J (2019) Physical and chemical pretreatment of lignocellulosic biomass. In: Second and third generation of feedstocks. Elsevier, Amsterdam, pp 143–196
33. Fengel D, Wegener G (1984) Wood: chemistry, ultrastructure. Reactions 613:1960–1982
34. Sirviö JA, Kolehmainen A, Liimatainen H, Niinimäki J, Hormi OE (2014) Biocomposite cellulose-alginate films: promising packaging materials. Food Chem 151:343–351
35. Naskar A, Khan H, Sarkar R, Kumar S, Halder D, Jana S (2018) Anti-biofilm activity and food packaging application of room temperature solution process based polyethylene glycol capped Ag-ZnO-graphene nanocomposite. Mater Sci Eng C 91:743–753