A review of injection-molded natural fiber-reinforced polymer composites

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Abstract

For the last couple of decades, researchers have been trying to explore eco-friendly materials which would significantly reduce the dependency on synthetic fibers and their composites. Natural fiber-based composites possess several excellent properties. They are biodegradable, non-abrasive, low cost, and lower density, which led to the growing interest in using these materials in industrial applications. However, the properties of composite materials depend on the chemical treatment of the fiber, matrix combination, and fabrication process. This study gives a bibliographic review on bio-composites specially fabricated by the injection-molding method. Technical information of injection-molded natural fiber reinforcement-based composites, especially their type and compounding process prior to molding, are discussed. A wide variety of injection-molding machines was used by the researchers for the composite manufacturing. Injection-molded composites contain natural fiber, including hemp, jute, sisal, flax, abaca, rice husk, kenaf, bamboo, and some miscellaneous kinds of fibers, are considered in this study.

Keywords: Natural fiber, Bio-composites, Injection molding, Compounding process

Introduction

Researchers are being attracted to study the fabrication of bio-composites because of the growing interest in using these composites. It is because the bio-composite material possesses some magnificent qualities when contrasted with that of synthetic fiber based. Fibers can be harvested from renewable resources and provide efficient stress transfer due to having along aspect ratio. Natural fibers can be of three types: animal, plant/vegetable, and mineral. Plant/vegetable fibers are the most viable fiber to work as a reinforcement of composite materials. Among all plant fibers, hemp, jute, sisal, flax, abaca, kenaf, bamboo, rice husk, etc., have caught attention (Bledzki & Gassan, 1999; Li et al., 2000; Satyanarayana et al., 1990; Hornsby et al., 1997; Hepworth et al., 2000; Rozman et al., 2000; Sinha et al., 2020; Singh et al., 2018; Adeniyi et al., 2019; Tholibon et al., 2019).

Evaluation of composite materials, their advancement in both structure and manufacturing technology, had been a milestone in material history. Two materials that are distinctive physically and chemically would create composite materials. This shows completely different properties from their constituents. Between the two materials, one is lighter, and the other is stronger. The former is known as matrix, while the latter is known as reinforcement. Matrix generally works with exchanging stress between reinforced fibers and protects them from outside harm. On the other hand, reinforcement improves hydrophobicity, durability, wettability, firmness of the composites, and their various strengths (Joseph et al., 1996; Chandramohan & Marimuthu, 2011; Lau et al., 2018; Sarikaya et al., 2019; Huang & Young, 2019; Espinach et al., 2017; Jeyapragash et al., 2020; Jariwala & Jain, 2019; Le Bourhis & Touchard, 2021; Dasore et al., 2021).

The problem with using natural fibers as reinforcement is that they do not provide much adhesion to the polymers. However, chemical treatments of the fiber surface can mitigate this. Researchers have tried various types of chemical treatment such as alkaline, silane, acetylation, acrylation, maleated coupling agent, and so on (Fiore et al., 2015; Liu et al., 2019; Sood & Dwivedi, 2018; Chung et al., 2018; Punyamurthy et al., 2014; Anbupalani et al., 2020). This surface treatment process of fiber substantially improves the attachment between the polymer and fiber, which brings out better material characteristics.

Another critical factor that plays a vital role in composite properties is the manufacturing process. Prior to manufacture, the fiber and matrix should be compounded. Many researchers have adopted different compounding or mixing techniques. Single/twin screw extruder, two roll mill ball machine, k-mixer, etc., are some common types of machines used to compound fiber and polymer. The compounded materials are then transferred for the manufacturing process. Different composite fabrication processes are shown in Fig. 1.

Among various composite manufacturing processes, injection molding is famous for mass production. Apart from this, other familiar processes are pultrusion, hand layup, vacuum-assisted resin transfer molding (VARTM), etc. (Elkington et al., 2015; Balasubramanian et al., 2018; Tamakuwala, 2020; Baran et al., 2017; Jaafar et al., 2019). This paper deals with the composite that had been fabricated using the injection-molding process. Thermoplastics produced by injection-molding technique have been utilized for many decades, ranges from small household staffs to extreme performance automobile parts (Wong & Mai, 1999; Shon & White, 1999; Schut, 2002a; Schut, 2003; Fara & Pavan, 2004; Thomason, 2002; Miklos & Gregory, 2003). Low wear and tear of tools, minimization of cycle time, recycling convenience, etc., are the significant advantages of natural fiber-based composites. In addition, thermoplastics-based on mineral fillers with ash residue expose a significant characteristic as energy can be recovered from the composites (Nyström, 1999/2000).

In the case of the closed mold composite manufacturing process, the injection-molding technique leads to other thermoplastics and thermosets manufacturing processes. Numerous researchers studied the feasibility of natural fiber composites fabricated by this technique focusing on the application in the industrial sector. This study represents a comprehensive and rigorous review of the previous studies. It depicts the research works by different researchers on key features of the IM process, and its application in fabricating natural fiber-reinforced composites.

Injection molding

Injection molding (IM) had a fast development because of the advancement of the new application zones such as automotive, hardware/apparatuses, medical, and bundling enterprises. The intricacy of the IM procedure requests a greatly improved comprehension of the material conduct during the fundamental phases of the procedure, the physical phenomena occurring, and its connection to the properties and execution of the last formed part (Fernandes et al., 2018). IM can be performed with a vast gathering of materials, including metals, glasses, elastomers, confections, and most generally thermoplastic and thermosetting polymers (Mohan et al., 2017). Today more than 33% of polymeric items are created with the utilization of IM (Osswald &

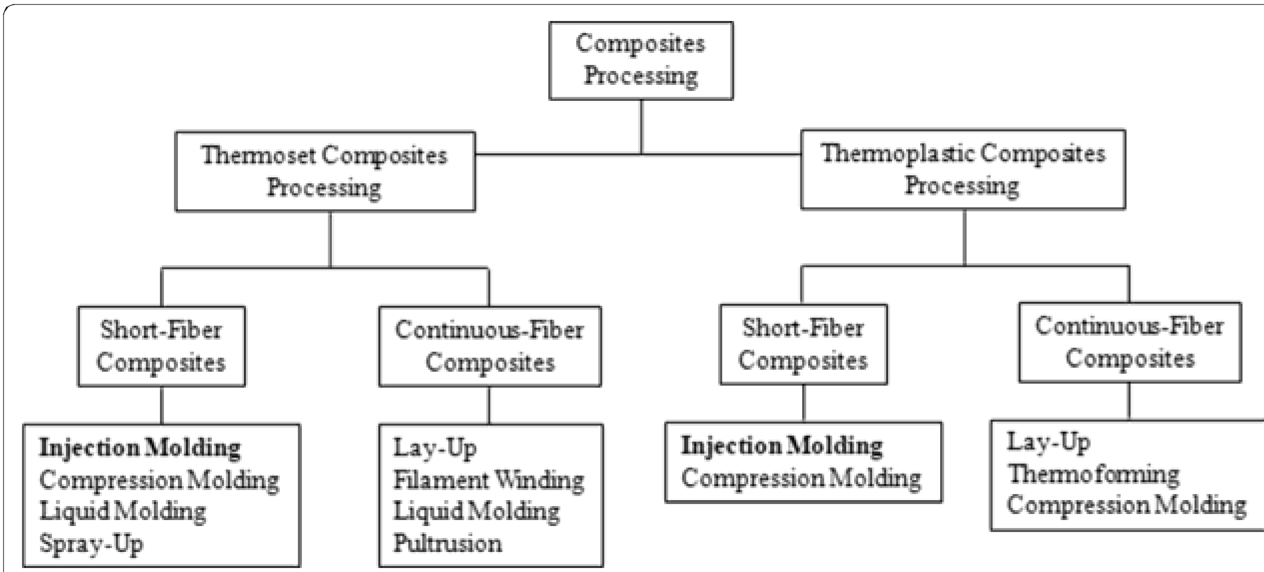

Fig. 1 Major polymer matrix composites fabrication process

Hernández-Ortiz, 2006). The entire procedure is confounded due to the complex thermo-mechanical changes of molten liquid polymer. After selecting the suitable and appropriate materials, generally, the IM process consists of the following cyclic process:

(i) Charging the cylinder
(ii) Mold closing
(iii) Polymer plasticization
(iv) Injection/pressure
(v) Cooling
(vi) Ejection or removal of the finished

The quality of the final product is crucial in IM process as this technique is mostly used for mass production. Compounding is one of the critical operations which play a significant role in the outcome of the IM process. Compounding can be referred to as a process of melt blending of polymers and other additives (natural fibers in this regard) to enhance the better mechanical properties of the composite. Large, toll, and special compounders are available in the market to provide proper function as per requirement. Usually, in the compounding process, long fibers are fed to the near end of the extruder to mix with the appropriate matrix (polymer). After compounding, the product in the form of granules is fed into the IM machine's hopper. Single and twin-screw extruders are the most used compounding machines available in the market. A typical flow-process chart to prepare natural fiber-based composite products using the IM process is given in Fig. 2.

Many researchers have been working for a long time to introduce more techniques in the IM process and make it more efficient. Teraoka (Shoichi, 1968) invented a new and valuable injection-molding machine with an injector with a plurality of heads that may be selectively engaged with a plurality of mold elements. Roger (Roger, 1954) made an invention to provide in a clamp having a double-acting clamping piston and cylinder and having a double-acting elevating or traversing piston and cylinder, an arrangement such that injection may be provided for, either axially through one platen or laterally at the parting plane. Laczko (Laczko, 1975) made development to give an improved control intends to persistently and successfully observe the consistency and nature of products created by an IM machine. Havlicsek and Alleyne (Havlicsek & Alleyne, 1999) inspected the controlling technique of an industrial injection-molding (IMM) machine. Such kind of machine is suitable for mold-filling and mold-packing process. Dinerman and Steffens (Dinerman & Steffens, 1991) introduced a positive action shut-off valve to provide correspondence between a valve inlet and outlet. Piotter et al. (Piotter et al., 1997) updated an IM machine outfitted with a unique control unit. The manufacturing apparatus temperature can be kept above the liquefying temperatures of the polymers within the injection time frame. Matsuda et al. (Matsuda et al., 1990) presented an invention of an IM which injects a liquefied resin into the cavity of a mold to form plastic moldings. Rees et al. (Rees et al., 1982) made a turret type IM machine for facilitating the separation of freshly molded work pieces from projections or cores of

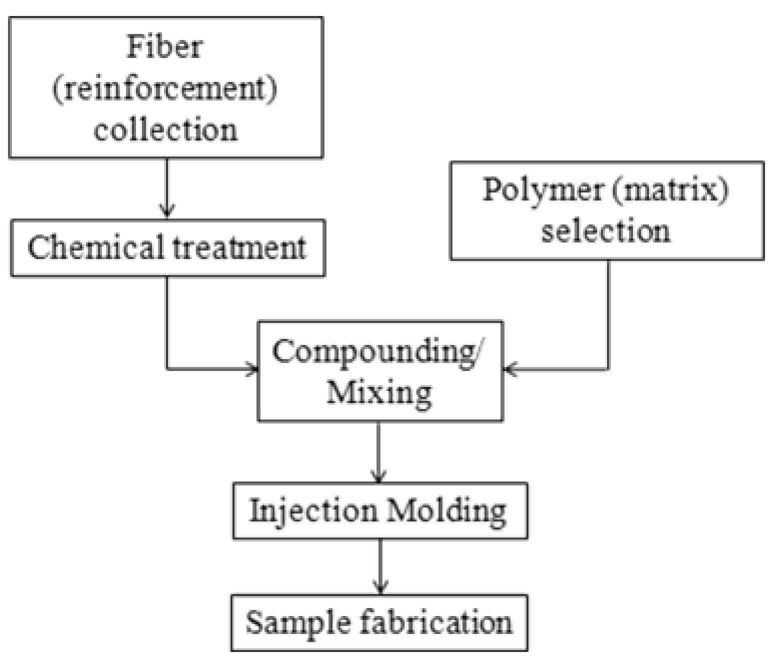

Fig. 2 Flowchart of IM process to prepare natural fiber-based composites

a turret on which they are retained after the mold has opened. Boehm et al. (Schad, 1984) presented a type of two-shot IM, where the primary shot structures the key button's outside surface. This is "shell first" two-shot IM. Schadn (Schad, 1986) invented "hot runners" for supplying hot molten plastic material to several mold cavities under controlled pressure and temperature conditions and with generously stream rates. Glaesener (Glaesener & Kestle, 1997) gave securing and clamping assembly to use with the bars of both singular and tandem IM machines. Wenger (Karl, 1964) improved IM, particularly in die closing, locking, and sealing means for such machines. The machine of his invention is particularly suited for molding shaped articles consisting of thermoplastic material, but the machine is equally useful for casting metallic objects. Schad and Pocock (Schad & Pocock, 1989) developed an IM especially for empty plastic materials which are blow formed into containers. A nonlinear mathematical model has been developed by Chiu et al. (Chiu et al., 1991) based on the Reynolds transport theorem to investigate the mold filling process. Such theorem is used to explain the polymer stream elements. Through a closed conduit, the filling process of the mold is estimated by the transient flow phenomenon. Sadeghi (Sadeghi, 2000) contemplated the prospect of anticipating the adequacy of the injection-molded parts using an ANN model and dependent on CAE software simulations. Schmidt (Schmidt, 1994) introduced an invention relates to the IM machine of the hot runner type. A bimetallic clamp arrangement has taken place in the arrangement to confirm a hot element located in a specific position around a nozzle body prior to feeding molten materials to a mold cavity. Galt et al. (Galt et al., 1998) invented a hydraulic IM machine that improved and more straightforward sound insulation. As the thickness of the demolded material varies with the requirement, it is impossible to directly compare IM cycle time and polymerization time (Piotter et al., 1997). Ribeiro (Ribeiro, 2005) developed a system to monitor in-process data, which can react rapidly to unsettling influences. Thiriez and Gutowski (Thiriez & Gutowski, 2006) made an environmental investigation of IM, which reveals that the type of IM machine (hydraulic, hybrid, or all-electric) has a significant effect on the specific energy consumption (SEC). Mianehrow and Abbasian (Mianehrow & Abbasian, 2017) measured the SEC of IM machines six in numbers and the EC profile during one complete cycle of the IM process. They investigated the influence of various parameters related to the machine and process on EC. Furthermore, they provide favorable circumstances of energy saving in the IM process. Gaub (Gaub, 2015) suggested that an automated, digitally networked cyber-physical production system would be cost-effective to create single-unit batches. They used the combination of IM, additive manufacturing, and "Industry 4.0" technologies.

Zhang et al. (Zhang et al., 2019) introduced the idea of cloud manufacturing (CMfg) in the IM-based industry. Madan et al. (Madan et al., 2015) concentrated on IM, where energy can play a vital role as a sustainability indicator. They proposed the guideline for the unit manufacturing process as (i) estimation, (ii) performance evaluation and benchmarking, and (iii) improvement. Kumar et al. (Kumar et al., 2016) went through a comprehensive analysis focusing on handling factors of polymer injection-molding (PIM) technique to enhance the casting of HDPE/cenosphere composites. Scluf et al. (Schift et al., 2000) have demonstrated that the combination of hot embossing and IM process can be performed to produce nanostructures. Link et al. (Link et al., 2019) disclosed some methods of operating an IM machine: (a) releasing a clamping pressure holding a first mold section and a second mold section together. The first mold section is mounted to a movable platen, and the second is mounted to a stationary platen. The method further includes (b) translating the movable platen in an opening direction away from the stationary platen to open the mold. The translating step includes translating the movable platen from a mold-closed position to an over-travel position spaced axially apart from the mold-closed position. The method further comprises (c) translating the movable platen in a closing direction opposite the opening direction from the over-travel position to a transfer position axially intermediate the mold-closed position and the over-travel position, and (d) moving a take-out device from a retracted position to an advanced position. The take-out device is clear of the first and second mold sections when in the retracted position, and the take-out device reaches between the first and second mold sections when in the advanced position for receiving articles from the first mold section when the movable platen is in the transfer position. The method further includes (e) transferring articles from the first mold section to the take-out device. The articles are received in retained engagement in the take-out device when the take-out device is in the advanced position, and the movable platen is in the transfer position. Ohba et al. (Ohba et al., 2009) proposed a novel sensorless force-control technique where the reaction torque observer measures the reaction torque instantly and perfectly without any effect of torsion. Kuo and Chang suggested a turbo injection mode (TIM) for a pivotal transition engine that can provide specific injection force onto a compactly designed IM machine. Figure 3 illustrates the two-wye-wye winding structure of such a machine, and it can be operated in two distinct levels of speed range (Kuo & Chang, 2015).

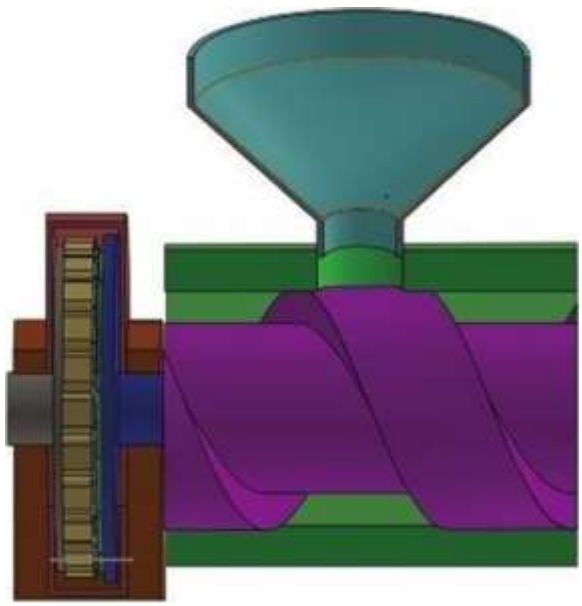

Fig. 3 Axial-flux motor (on the left-hand side) in the plastic injection-molding machine (adapted from Kuo & Chang, 2015)

Composites fabricated by injection molding

IM process is a popular manufacturing method for mass production. High processability is the key concern in favor of IM though the reinforcement fiber degrades during the process. A wide number of natural fiber can be used as a reinforcement for the composite in injection molding. Injection-molded polymers either with natural reinforcement or alone had been used for many years (Schut, 2002b; Hashemi, 2002). Types of IM machines had been used for the composite processing, which is summarized in Table 1.

Flax fiber based

Arbelaiz et al. (Arbelaiz et al., 2006) interrogated the fiber treatment influence on the thermal stability of flax fiber/polypropylene composites. They used Battenfeld Plus 250 IM for the fabrication of composites. Prior to IM, the mixture of flax fiber and polypropylene was pelletized as well as dried. Haake Rheomix 600 complied with two Banbury rotors internal mixer had been used for the compounding of the materials. Harriëtte et al. (Bos et al., 2006) demonstrated the mechanical characteristics of flax fiber/polypropylenematerials. In their study, fibers and polymers were kneaded by Haake Rheomix 3000 batch kneader and compounded by Berstorf ZE 40 co-rotating twin-screw extruder, then molded using Demag Ergotech 25–80 compact type IM machine. Li et al. (Li et al., 2006) discussed the influence of fiber percentage on flax fiber/high-density polyethylene composite. A twin-screw extruder was occupied for compounding, and the mixture was fed into a Battenfeld IM machine. The mixtures were grounded in a grinding mill before extrusion, and the extrudates were chopped into pellets before IM. Guillermo Cantero et al. (Cantero et al., 2003) discussed the impact of chemically treated fiber on mechanical characteristics and wettability. Before molding, flax fiber and polypropylene were extruded in a conical twin-screw extruder. Battenfeld Plus 250 IM machine was used to prepare the specimen. Bax and Müssig (Bax & Müssig, 2008) fabricated flax/PLA composite and Cordenka/PLA composite by a Battenfeld UNILOG 4000 type IM machine. A shredder had been used for making the pellets. Jerico Biagiotti et al. (Biagiotti et al., 2004) investigated the impact of chemical refinement of fiber on the polypropylene/flax fiber composite properties. Initially, a blade mill had been used to defibrillate the flax pulp and make them dried in an oven. The defibrillated flax and polypropylene were fed into a twin-screw extruder (HaakeRheomex CTW 100) for compounding and then molded in a Battenfeld Plus 250 IM machine. The granulated compound can be effectively prepared on a typical IM machine. At the mixing and molding process, the low thermal stability of vegetable fibers was considered (Aurich et al., 1998; Wielage et al., 1999). Fiber orientation state of composites has been investigated. Maximum stock and mold temperature was kept 220 °C, and 50 °C, respectively. A total of 60-MPa pressure has been occupied as the holding pressure, and the flow front velocity of 80 mm/s was applied. The bio-composite specimen of 2 mm thickness is depicted in Fig. 4 (Aurich & Mennig, 2001).

Mondragon et al. (Arbelaiz et al., 2005) analyzed the characteristics of flax fiber/PPbio-composites. Polypropylene along with dried and chemically treated flax fibers passed through a Haake Rheomix 600 with two Banbury rotors type internal mixer followed by extrusion in a Haake Rheomex CTW100 type twin screw extruder. The specimen was prepared in a BattenfeldPlus 250 IM machine. Gong et al. (Pilla et al., 2009a) studied static and dynamic characteristics, cell morphology, and crystallization behavior by varying fiber and silane content in polylactide–flax fiber composite. The oven-dried mixtures were blended in a thermo-kinetic mixer (k-mixer), and after that, the mixed materials were fed into Davis–Standard twin-screw extruder. They investigated the sample properties prepared by varying the fiber content (ranges 1-20%). Bledzki et al. (Bledzki et al., 2008) interrogated the impact of chemically treated (acetylation) fiber on flax fiber/polypropylene composites. Raw materials were mixed in an HM40-KM120 type Henschel heat-cooling mixer system. Then dried granules were made from those mixtures, and test samples were fabricated. Thermo-mechanical properties of short flax fiber/PLA composites have been investigated by Laura et al. (Aliotta et al., 2019). The raw materials were

Table 1 Types of IM machines used to fabricate different natural fiber-based composites

Brand	Model	Composite constituents	L/D ratio	Manufacturer name
Battenfeld	Plus 250	i. Flax fiber/polypropylene ii. Flax fiber/polyethelyne	20	Wittmann Battenfeld
	UNILOG 4000	i. Flax fiber/polylactic acid ii. Cordenka/polylactic acid	22.1	
	Plus 350	Rice husk/polypropylene	20	
	HM 60/210	i. Wood flour/ecoflex ii. Wood flour/polylactic acid iii. Wood flour/ecovio iv. Wood flour/bioflex v. Wood flour/tenite propionate	22	
Cincinnati Milacron	33 T	i. Jute fiber/polypropylene ii. Wood flour/polypropylene iii. Wood flour/polylactic acid	-	Milacron Inc.
	85 T	i. Hemp fiber/cellulose acetate ii. Hemp fiber/soy protein bioplastic	30	
	Molder	Kenaf fiber/polypropylene	-	
Demag Ergotech	25-80 Compact	Flax fiber/polypropylene	24	Sumitomo Shi Demag
	100 T	Jute fiber/polypropylene	20	
Ray-Ran		Wood flour/polyethylene	-	RAY-RAN Test Equipment Ltd.
Arburg	Allrounder 320S	Flax fiber/polypropylene	23.3	ARBURG
	Allrounder 270S	Roselle fiber/polypropylene	24	
	40 T	Kenaf fiber/PP/MAPP	-	
	100 T 320C	Micro sized flax fiber/PA6	20	
	500-210	Coir fiber/banana fiber/polypropylene	33	
PLASTER ET-40 V		Jute fiber/polylactide	40	Toyo Machinery & Metal Co. Ltd.
Ferromatik Milacron	K40/80	Hemp fiber/poly(3-hydroxybutyrate-co-hydroxyvalerate)	22	FERROMATIK
	FM 85	Abaca fiber/polylactic acid	25	
Reed Prentice 100 T		Wood flour/polypropylene	-	Reed-Prentice Corporation
Little-Ace I		Abaca fiber/polyester	40	Tsubako Co. Ltd.
Sandretto	Micro-30	Jute fiber/polypropylene		DTL Machinery
	60 T	Sisal fiber/starch	19	
ROMIPratica130T		Sisal fiber/polypropylene	22	ROMI
Sumitomo	SE 50D	Bamboo fiber/poly(3-hydroxybutyrate-co-3-hydroxyvalerate)	20	Sumitomo Corporation
	55 US SE DU	Wood fiber/plastic	23	
TTI-80		Sisal fiber/polypropylene	-	Dong Hua Machinery Co. Ltd.
Engel	e-Victory	i. Hemp fiber/polypropylene ii. Coir fiber/polypropylene	21	Engel Electronics
	ES 80/25	Date palm/polypropylene	18.2	
	23/40	Hemp fiber/polypropylene	-	
	ES 80/20 HLS	Wood flour/polypropylene /Polylactic acid	23	
	e-Max 440/ 100	i. Banana fiber/ABS ii. Banana fiber/HIPS iii. Banana fiber/HDPE	-	
SM-50		Wood flour/polypropylene	25	Super Master (Chen-Hsong Company)

Table 1 Types of IM machines used to fabricate different natural fiber-based composites *(Continued)*

Brand	Model	Composite constituents	L/D ratio	Manufacturer name
BOY	50 T	Sisal-PP	20	BOY
	15S	i. Hemp fiber/polypropylene ii. Wood flour/polypropylene	18	
	50A	Kenaf fiber/polypropylene	18	
JSW100 T		i. Kenaf fiber/polylactic acid ii. Rice husk/polylactic acid	22.5	Japan Steel Works
TOYO PSS TI-30F6		Jute fiber/polypropylene	-	Toyo Machinery & Metal Co. Ltd.
DH-90		Bassalt fiber/polybutylene succinate	-	Tederic Machinery Co. Ltd.
Endura-60		i. Hemp fiber/polylactic acid ii. Sisal fiber/polylactic acid	19	Electronica Plastic machines
HAAKE	Minijet II	Hemp fiber/polylactic acid Flax fiber/polylactic acid Bamboo fiber/polylactic acid	25	Thermo Electron Corporation
Meteo	40	Wood flour/polypropylene	-	Mateu&Solé, S.A
	270/75	Flaxseed flour (FSF)/polylactic acid	-	
WZ-10G		Sisal fiber/polypropylene	-	Shanghai Xinshuo Precision Machinery Co. Ltd.
SZS-20		Abaca fiber/PP/eggshell powder	20	Wuhan Ruiming Experimental Instrument Manufacturing Co. Ltd.
HAIXING		Kenaf fiber/polypropylene	16	HAIXING Company
Haitian	MA600 II/130	Rice husk/polypropylene	33	Absolute Machinery
NIOOB 11		Kenaf fiber/xGNP/polypropylene	30	Japan Steel Works Muraron
ES-1000		Coir fiber/polylactic acid	-	NISSEI Plastic Industrial Co. Ltd.
Zerus 900		Birch fiber/high-density polyethylene	-	ZHAFIR Plastics Machinery

blended in a co-rotating conical twin-screw extruder before preparing the composite specimen in Haake MiniJet II mini IM machine. Aguero et al. characterized the green composites fabricated from flaxseed flour (FSF) and PLA (Agüero et al., 2020). A twin-screw co-rotating extruder from DUPRA S. L. was employed to compound the different formulations. A Meteo 270/75 IM machine was used to manufacture the pieces from the melt-compounded pellets. Mechanical properties of flax fiber-based nanocomposites have been examined, where PA6 was used as the matrix (Shao et al., 2019). A twin-screw extruder was used to prepare the compound prior to

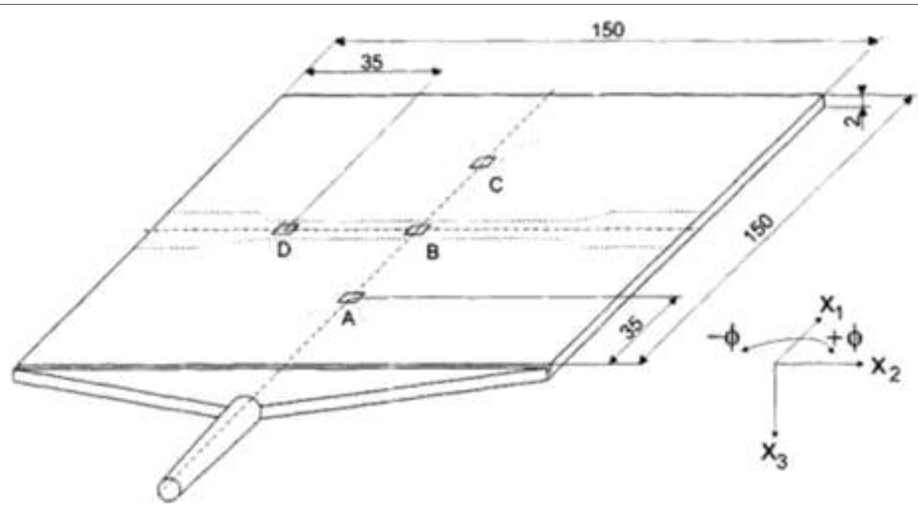

Fig. 4 Fabricated specimen with locations of fiber orientation (dimensions in mm) (adapted from Aurich & Mennig, 2001)

injecting in a 100 ton ARBURG-420C IM where the machine was equipped with a microcellular foaming system.

Jute fiber based

Rana et al. (Rana et al., 2003) fabricated jute fiber polypropylene composite to observe the influence of fiber loading, impact modifier, and compatibilizer on the composite. A high shear K-mixer has been used for better mixing, and dried granules were made prior to injecting in 33 T Cincinnati Milacron IM machine. Another jute/polypropylene composites had been fabricated by Mäder et al. (Gao & Mäder, 2006) to study the impact of modifying the matrix. The composite fabrication was commenced by compounding jute, polypropylene and maleic anhydride graft polypropylene together on a ZSK30 type co-rotating twin-screw extruder. Ergotech 100 TIM machine was used to make the required samples. Arao et al. (Arao et al., 2015) presented the impact of long fiber pellets on the characteristics of jute fiber/polylactide composite materials. The final output was fabricated in a PLASTER ET-40 V type IM machine. Before injection molding, fiber with all additives was compounded in a ZSK-18 type twin screw extruder. They employed two different configurations while compounding for two specific purposes: (i) reduce the shear stress and (ii) improve the overall fiber dispersion. Yang et al. (Yang et al., 2011) observed the impact of fiber immersion into hot water and fiber contents on the tensile characteristics of jute/polypropylene composites. A 30 T TOYO PSS TI-30F6 IM machine had been used in their study to fabricate two types of dumbbell-shaped specimen (one is made of pure polypropylene, and the other was made of jute-polypropylene together). Thomason (Thomason, 2010) used a 200 T Cincinnati Milacron IM machine of a capacity 225 g barrel to prepare jute/polypropylene composites. Their research also prepared glass fiber reinforced polypropylene composite based on previous studies (Fernandes et al., 2018; Mohan et al., 2017). A comparison has been made between these two composites regarding their dependence on interfacial strength. Hasan et al. (Rahman et al., 2008; Rezaur Rahman et al., 2010) used post-treatment of the jute/polypropylene composites to improve the physio-mechanical properties. A single screw extruder was utilized for compounding jute and polypropylene, and the product was ground in a grinding machine prior to IM. Cabral et al. (Cabral et al., 2005) figured out the structure-properties relationship of jute/polypropylene composites. A twin-screw extruder was used for compounding, and specimens were prepared using a Micro-30 Sandretto IM machine. Jiang et al. investigated the effect of hydrothermal aging on injection-molded short jute fiber/PLA composites (Jiang et al., 2018). The jute fibers and PLA were blended using an IM machine before the specimen was prepared using SHJ-20 twin-screw extruder. Pailoor et al. examined the effect of chopped/continuous fiber, coupling agent and fiber ratio on the jute fiber/PP composites (Pailoor et al., 2019). Chopped jute fiber of length 1-2 mm and PP pellets along with MAPP was fed into a STEER Omega-40 twin-screw co-rotating extruder to prepare the compounded pellets.

Sisal fiber based

Concerning IM of sisal fiber/polypropylene composites, the problems found are (i) poor interfacial bonding between raw materials and (ii) escalated melt flow viscosity (Joseph et al., 1999; Fung et al., 2002). High injection temperature is needed to mitigate high melt viscosity-related problems. A pre-impregnation method is introduced by Li et al. (Fung et al., 2003), which involves feeding dry sisal fiber through a unique die configuration, as shown in Fig. 5. A Brabender single screw extruder was connected to the drying setup. After impregnation, the extruded materials were cut, pelletized, and finally fed into the injection-molding machine to fabricate the composites.

Sun et al. (Sun et al., 2010) analyzed the impact of material optimization on the characteristics of bio-composite materials. A SK-1600B two-roll mill machine was used for compounding, and the composites were manufactured using a TTI-80 device. Krishnan Jayaraman (Jayaraman, 2003) developed a simple manufacturing method of fabricating sisal fiber-based polypropylene composites to minimize the fiber degradation. A BOY injection molder with a capacity of 50 tonnes has been used and the barrel temperature set at 185 °C for preparing the composite. Li et al. (Chow et al., 2007) studied moisture absorption of sisal/polypropylene composite. Sisal fiber was chemically treated with MA-g-PP had been melting blended with polypropylene into a single screw extruder using a pre-impregnation technique. Li et al. (Xie et al., 2002) systematically investigated the mechanical properties, crystalline structure, thermal properties, morphology, melt mixing characteristics. In the process, the chopped sisal fiber and the polypropylene were mixed in an internal mixer attached with a Brabender Plasticorder. Bernal et al. (Alvarez et al., 2006) interrogated the impact of microstructure on the mechanical characteristics of sisal fiber/starch composites. In their study, the raw materials were directly fed into a Sandretto 60 T IM machine. Sabu Thomas et al. (Kalaprasad et al., 1997) investigated the enhancement of the mechanical characteristics of sisal/polyethylene composite by adding glass fiber. A hand-operated ram type IM was used for preparing the composites. Fung et al. (Fung et al., 2002) studied the characteristics of sisal fiber/polypropylene bio-composites by improving

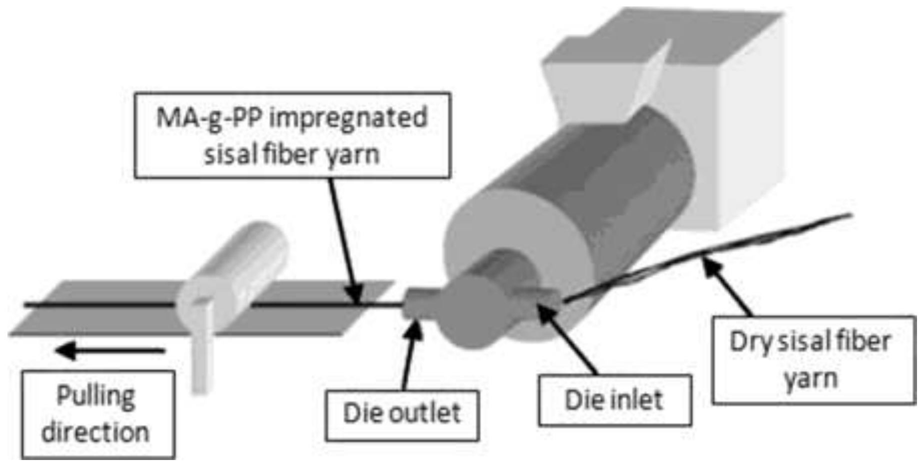

Fig. 5 Experimental setup for the impregnation of sisal fiber yarns with MA-g-PP (adapted from Fung et al., 2003)

the fiber interface. They manufactured the composites by melt blending followed by IM. Vázquez et al. (Alvarez et al., 2004) presented the melt rheological properties of sisal fiber composites. A Sandretto 60 T IM machine was used in this study.

Saurabh Chaitanya and Inderdeep Singh (Chaitanya & Singh, 2017) explored the direct IM method for manufacturing PLA-based sisal fiber bio-composites and made a comparison with the extrusion IM method. Endura-60 type IM machine had been used in their study. The raw materials were mixed in a mechanical agitator for the direct IM process depicted in Fig. 6. On the other hand, in the extrusion IM process (Fig. 7), a single screw extruder was used. It had been concluded that direct IM is suitable for short fiber whereas extrusion IM is suitable for both short and long fiber.

KC et al. (Kc et al., 2016) worked with optimizing IM parameters using the Taguchi method to reduce shrinkage behavior of sisal/glass fiber hybrid composite. Six parameters such as (i) holding time, (ii) holding pressure, (iii) injected pressure, (iv) mold and (v) melt temperature, and (vi) cooling time were identified that influence flow and cross-flow shrinkage. ROMI Pratica 130 type IM machine had been used to manufacture the bio-composites based on the previous study (Birat et al., 2015). Arbelaiz et al. (Orue et al., 2016) discussed the influence of various chemical treatments on both sisal fibers and sisal/PLA composites. As part of the composite fabrication, the fiber and matrix were compounded in a Haake Rheomix 600 melt mixer and were carried out in a HAAKE Minijet IIIM machine. Dog bone type specimens of the composite were fabricated through this process. Z. Samouh (Samouh et al., 2019) investigated the mechanical and thermal characterization of sisal/PLA composites with various weight percentages of fiber (5%, 10%, and 15%). The PLA biodegradable polymer

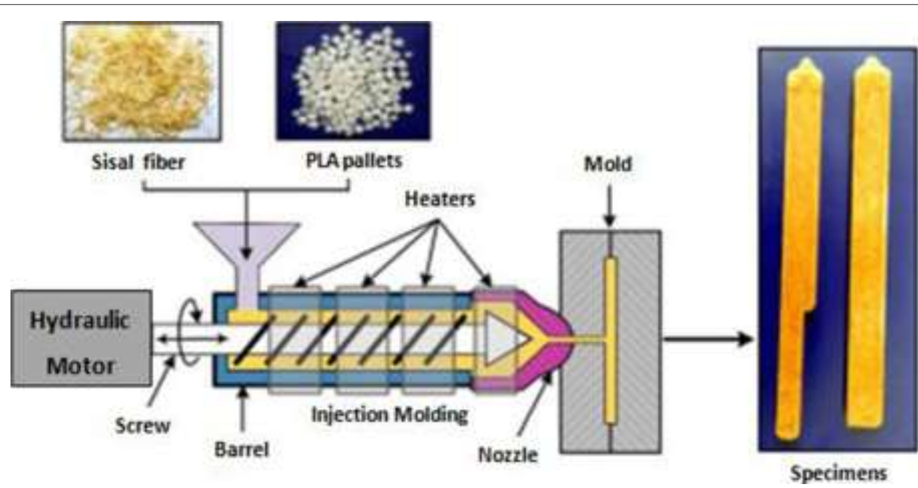

Fig. 6 Schematic of direct-injection-molding process (adapted from Chaitanya & Singh, 2017)

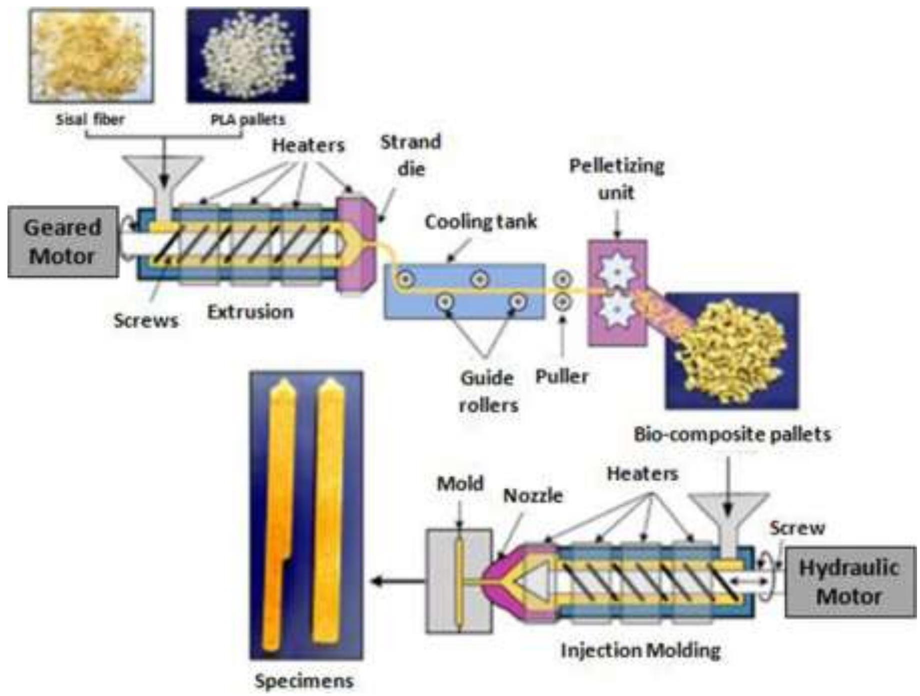

Fig. 7 Schematic of extrusion-injection-molding process (adapted from Chaitanya & Singh, 2017)

and the fiber were mixed using Labtech LTE 26-44 twin-screw extruder. The specimens were molded by an Arburg Allrounder 270-II IM machine. Chaitanya (Chai- tanya et al., 2019) figured out the recyclability character- istics of sisal/PLA biocomposites (Chaitanya et al., 2019). Sisal fiber having fiber weight fraction of 30% recycled using a single screw extruder and molded using an Endura 60 IM machine. It was found that the biocompo- sites recycled up to third recycle for low to medium strength non-structural application. To inspect the changes of intrinsic mechanical properties of sisal fiber/ PP biocomposites, Sun and Wu (Sun & Mingming, 2019) conducted a study on the sol-gel modification of the sisal fiber (Sun & Mingming, 2019). A WLG-10G mini twin-screw extruder was used to extrude the resin, and the specimen was prepared using a WZ-10G mini- IM machine.

Hemp fiber based

Suhara and Mohini (Panthapulakkal & Sain, 2007) assessed various characteristics of hemp/glass/polypro-pylene composites. Melt blended compounds were dir-ectly fed into the IM machine. Injection temperature was 205 °C, whereas injection time, cooling, and mold opening times were 8 s, 25 s, and 25 s, respectively. Kel-ler (Keller, 2003) studied the mechanical as well as com-pounding characteristics of hemp fiber-based bio-composites. Fiber and matrix were extruded in a co-rotating twin screw-type arrangement before feeding into a Ferromatik Milacron K40/80 IM machine.

Mohanty et al. (Mohanty et al., 2004) observed the in-fluence of processing techniques on the characteristics of hemp fiber/cellulose acetate bio-composites. Paticider was mixed with cellulose acetate to prepare pellets and compounded with chopped fiber in a twin screw-type extruder. The pelletized raw material was eventually molded in an 85 ton Cincinnati–Milacron press type IM machine. A sample of biocomposite is portrayed in Fig. 8. In another study (Mohanty et al., 2005), soya protein-based bioplastic was used as a matrix.

Mustapha et al. (Assarar et al., 2016) characterized the acoustic emission of damage of the composites that had been prepared from short hemp fiber and polypropylene. The specimens were supplied by the AFT Plasturgie Company which was elaborated by IM with a two-cavity mold. Pickering and Beckermann (Beckermann & Pick-ering, 2008) conducted fiber treatment and matrix modi-fication of hemp/polypropylene composite to evaluate its properties. The extruded raw material was molded in a BOY15-S IM machine. Qaiss et al. (Qaiss & Bousmina, 2011) investigated the thermal and mechanical charac-teristics of hemp fiber/polypropylene composite. The treatment procedure and the fabrication method of the composite had been followed by the previous work (Le Troedec et al., 2008; Rokbi et al., 2011; Qaiss et al., 2012; Qaiss et al., 2013; Arrakhiz et al., 2013). The specimen

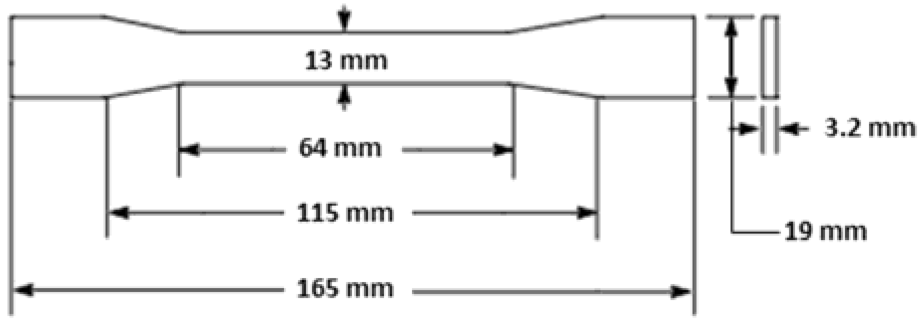

Fig. 8 The dimension of injection-molded sample preparing for mechanical and thermal testing (adapted from (Mohanty et al., 2005))

was prepared by Engel e-Victory type IM machine. Panaitescu et al. (Panaitescu et al., 2019) studied the characteristics of the alkali and alkali-silane-treated hemp fiber/PP composites. In the experiment, PP was mixed with five wt% MAPP and 15 wt% SEBS in a rotating mixture and compounded with fiber in Brabender DSE 20 twin-screw extruder. Engel 23/40 IM machine was used to prepare the specimen. It is found that the effect of hemp fiber length on the mechanical and thermal properties of PP/SEBS/hemp fiber biocomposites (Vinod & Anandajothi, 2020). The impact of hybridizing hemp fiber with recycled carbon fiber on the composite characteristics figured out by Shah et al. (Shah et al., 2019). The materials were processed into a composite using a Leistriz Mic 18/GI-40D co-rotating twin-screw extruder and pelletized with a Scheer Bay BT25 pelletizer. Eventually, the processed material was injected using a Technoplas hydraulic injection molder.

Abaca fiber based

Shibata et al. (Shibata et al., 2003) fabricated biocomposites from abaca fiber and polyester. Mixing was done in a twin rotary mixer, cut into small pieces, immersed in liquid nitrogen, dried, and fed into Little-Ace I Typedesk IM machine to prepare dumbbell-shaped specimen shown in Fig. 9.

Islam et al. (Rahman et al., 2009; Islam et al., 2010) assessed the mechanical properties of abaca/polypropylene composite and coir/polypropylene composite. Dried abaca/coir and polypropylene granules were pre-mixed and extruded for proper mixing using a single screw extruder to prepare the composites. The extrudates were again granulated using a grinding machine, and dried granules were fed into the IM machine to prepare the specimen. Bledzki (Bledzki et al., 2010) prepared a polypropylene composite where enzyme-modified abaca fiber was used as reinforcement. The abaca was treated first and then got mixed with polypropylene in a high-speed cascade mixer. Then, they were fed into a hot mixer to form hot agglomerate granules. The granules were then cooled, dried, and passed into the IM machine to prepare the composite sample. Bledzki et al. (Bledzki et al., 2009) studied the characteristics of abaca fiber/artificial cellulose fiber/PLA biocomposites. The composite had been fabricated by two processes illustrated in Fig. 10. First, PLA and fibers were extruded by a twin screw-type arrangement and then fed into a single screw extruder. After getting compounded two times, the compounded

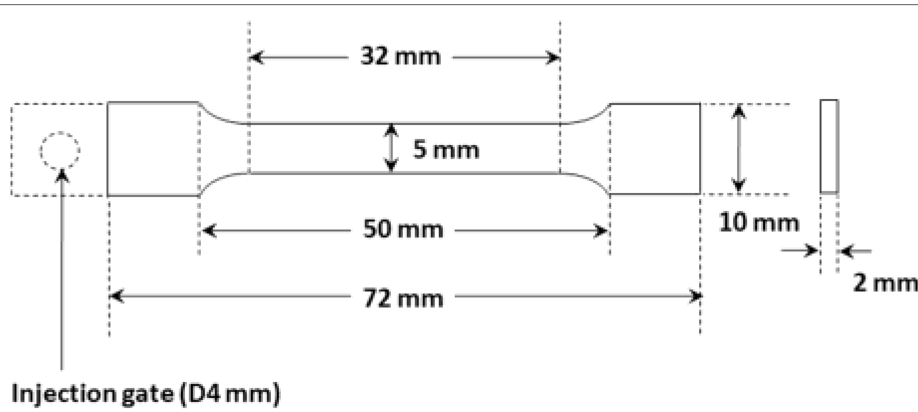

Fig. 9 Dumbbell-shaped specimen for the flexural test (the part shown by the dotted line was cut before measurement) (adapted from (Shibata et al., 2003))

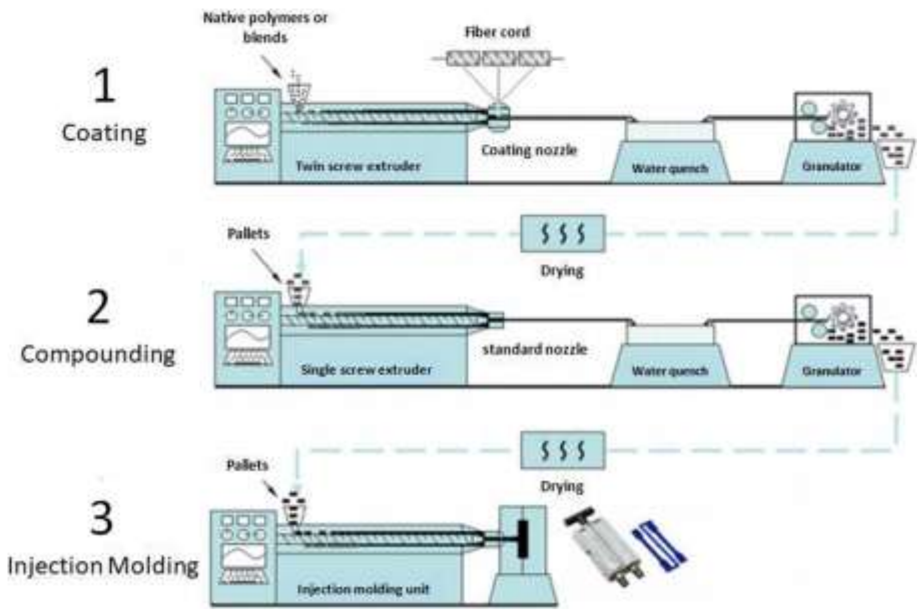

Fig. 10 Depicting of two-step extrusion principle (above) with successive injection molding (below) (adapted from Bledzki et al., 2009)

materials were pelletized, dried, and fed into the Ferromatik FM 85 type machine. The addition of bio-waste (eggshell powder) in the abaca fiber/PP composite improves thermal and mechanical properties (Mai Nguyen Tran et al., 2020). Abaca fiber of length 2-4 mm and PP fed the micro double cone SJZS-10B dual screw extruder hopper. The obtained pellets were molded in a SZS-20 injection machine for getting mechanical test specimens.

Kenaf fiber based

Anand et al. (Sanadi et al., 1994) examined the effect of reinforcing kenaf fiber into melted polypropylene polymer composite. The fiber and polymer were blended, dried and injection molded to fabricate the composite. A twin-screw extruder has been used for compounding the dried kenaf fiber and mixture of polypropylene and MAPP by Kamani et al. (Karnani et al., 1997). The compounded pellets were dried and injected in a 40 T Arburg plunger. Sanadi et al. (Sanadi et al., 1995) investigated the characteristics of kenaf/polypropylene composite produced by a Cincinnati Milacron Molder. Yussuf et al. (Yussuf et al., 2010) figured out a comparison among the thermal, biodegradable, and mechanical characteristics between kenaf fiber/PLA and rice husk/PLA composites. A homemade machine was used for crushing the fibers. Before blending, all materials were kept in desiccators to subside the moisture. A counter-rotating twin-screw extruder has been used as a compounder. The raw materials are then pelletized and fed into JSW–100 ton type IM machine. Subasinghe and Bhattacharyya (Subasinghe et al., 2015) evaluated the flammability and mechanical characteristics of kenaf fiber/polypropylene composites and analyzed the fiber length retention capacity of extrusion and IM processes. The twin-screw extrusion method was applied for compounding the fiber and matrix. The twin-screw extruder provides narrow residence time distribution and supplies uniform heat, thus reducing degradation (Zhang et al., 2009). A BOY 50A type IM machine was used to fabricate the composite. Kim et al. (Kwon et al., 2014) assessed the tensile properties of kenaf/PLA hybrid biocomposites and compared them with corn husk flour reinforced PLA composites. Mirbagheri et al. (Mirbagheri et al., 2007) studied the mechanical characteristics of wood flour/kenaf fiber/polypropylenebio-composites. A HAAKE internal mixer was used for compounding, and the mixture was directly fed into the IM machine. Nematollahi et al. (Nematollahi et al., 2019) studied the effect of surface treatment on morphological features of kenaf fiber/PP composites. Among various weight percentages of kenaf fiber, it is found that the 40% fiber, 56% PP, and 4% MAPP content showed a better result. The raw materials were blended in a Dr. Collins GmbH twin-screw extruder and molded using a HAIXING IM machine. It was investigated that, to obtain the complete interfacial load transfer, the length of kenaf fibers needs to be greater than the critical length being ~ 2.4 mm provided that perfect kenaf/PP interfacial interaction exists (Nematollahi et al., 2020). In the case of kenaffiber-based nano-biocomposites, the effect of chemical modification of the fiber has been studied by Idumah et al. (Idumah et al., 2019). The composites were melt-extruded utilizing a Brabender-PL-2000-Plastic-Coder counter-rotating twin-screw extruder. Specimens were prepared using the NIOOB-11 IM machine.

Bamboo fiber based

Liao and Thwe (Thwe & Liao, 2003) prepared the bamboo/glass fiber/polypropylene composites and investigated their durability. A torque rheometer has been used for compounding the raw materials. Tokoro et al. (Tokoro et al., 2008) provided instruction about improving the mechanical properties of bamboo/PLA composite. Okubo et al. (Okubo et al., 2009) developed a hybrid bio-composite based on bamboo fibers and microfibrillated cellulose reinforced poly lactic acid. The mixture of the materials was processed in a three-roll mill compounding machine. Then, they were fed into a micro-scale injection molder which is combined with a twin-screw extruding assembly. The molded composite sample is given in Fig. 11.

Jiang et al. (Jiang et al., 2008) interrogated the impact of nucleation agent and compatibilizer on bamboo fiber/ poly(3-hydroxybutyrate-co-3-hydroxyvalerate) bio-composites. Raw materials were passed through a HAAKE mixture and then were dried, were pelletized, and were transferred into Sumitomo SE 50D type IM machine for sample fabrication. 3D printing capability of bamboo fiber/PP/PLA composite has been assessed by Long et al. (Long et al., 2019). Dried BF, PP, PLA, and MAPP were blended using a co-rotating twin-screw extruder prior to feeding into the IM machine. Kumar and Tumu (Kumar & Tumu, 2019) investigated the prospect of bamboo powder-based bio-composites. Electron beam irradiated bamboo powder compounded with PLA and epoxide silane using a twin-screw extruder. The durability of bamboo fiber/PP composites was evaluated where the samples were exposed to natural weathering for 1 year before characterization (Fajardo Cabrera de Lima et al., 2020). The materials were mixed in HAAKE RheoDrive 7 Rheomix OS machine, and the specimens were obtained using HAAKE Minijet II IM machine.

Rice husk based

Aridi et al. (Aridi et al., 2016) and Ishak et al. (Ishak et al., 2001) examined the hydrothermal aging, morphological, and mechanical characteristics of rice husk/polypropylene composite. The whole preparation process is shown in Fig. 12. A Battenfeld BA350CD Plus type IM machine was used to fabricate the composite sample.

Rahman et al. (Ishak et al., 2001) evaluated the effect of using rice husk/high-density polyethylene bio-composite. Grounded rice straw and polyethylene were extruded in a co-rotating and intermeshing twin screw-type assembly. Jyoti et al. (Jyoti et al., 2021) examined that amorphous nanosilica from rice husk can reinforce PVDF polymer matrix. Then, the compounded materials were pelletized and injection molded to prepare the desired sample. Influences of the fiber geometry and orientation on the anisotropic behavior of the mechanical and thermal properties of rice husk/high-density polyethylene (HDPE) composites have been studied by Hao et al. (Hao et al., 2020). Before preparing the specimen, the raw materials were blended using a SJSH-30 twin-screw extruder and SJ-45 single screw extruder. Stress ratio plays a significant role on fatigue crack growth of rice husk/PP bio-composites (Hao et al., 2020). Betol BTS 40 has been occupied for melt-blending the materials, and the specimens were prepared using Haitian MA600 II/ 130 IM machine. Rice husk/PBS composite achieved 92% mass loss after 6 months of soil burial test confirms its biodegradability (Yap et al., 2021).

Wood fiber based

Kuo et al. (2009) discussed the impact of material composition on wood flour/polypropylenebio-composites. A

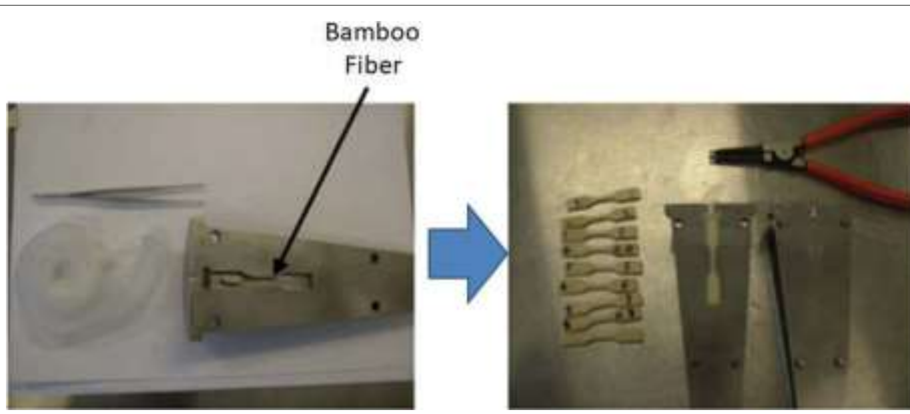

Fig. 11 Processing of model bamboo/MFC/PLA composites (left) bamboo fiber suspended in the injection mold using a piece of wood to center the fiber and (right) embedded bamboo fiber specimens after molding (adapted from (Okubo et al., 2009))

Fig. 12 Pallet preparation of rice husk/PP composites injection molding (Aridi et al., 2016)

SM-50 type IM machine to manufacture the composite. Stark and Rowlands (Stark & Rowlands, 2003) produced wood fiber/polypropylene composite and assessed its characteristics. A co-rotating, intermeshing twin-screw extruder was used for compounding the raw materials prior to molded in a Cincinnati Milacron 33 T IM machine. Bledzki and Faruk (Bledzki & Faruk, 2006) manufactured microcellular wood fiber-polypropylene composite where the use of different chemical foaming agents was investigated. Prior to IM, wood fiber and polypropylene were mixed by a high-speed mixer. Pilla et al. (Pilla et al., 2009b) fabricated bio-composites from recycled wood and polylactic acid. The raw material was mixed using a k-mixer and molded using a Cincinnati Milacron 33 T IM machine. Koubaa et al. (Bouafif et al., 2009) fabricated wood plastic composite in two stages. First, the wood particles were compounded with high-density polyethylene and molded in a reciprocating screw IM machine. Second, the raw materials were compounded in a co-rotating twin-screw extruder. Injection and hold pressure was 900 kPa. Cooling and holding time was set to 15 s and 4 s, respectively. Pilla et al. (Pilla et al., 2008) investigated the physical properties of polylactide-pine wood flour composites to assess their use considering the low material cost. Ichazo et al. (Ichazo et al., 2001) studied the variation of morphological, thermal, and mechanical characteristics of wood/polypropylene composite due to filler modification. Dried wood flour was mixed with polypropylene in a co-rotating twin-screw extruder and then 100 ton Reed Prentice IM machine was used to fabricate the test samples. Koubaa et al. (Migneault et al., 2009) discussed the impact of varied reinforcement size and pre-processing techniques on the characteristics of wood/plastic composites properties. The samples were prepared by Sumitomo 55-US ton SE-DU Series IM machine.

Ansari et al. (2017) investigated the anisotropic behavior of wood fiber/polypropylene composite. They used a 40-Meteo IM machine for molding the composite. They also studied a theoretical rheological performance by the Moldex 3D program. Figure 13 shows the outcome of the rheological study. Reinforcement alignment was homogeneous along with the sample (from the film gate to the end of the mold).

Sykacek et al. (Sykacek et al., 2009) extruded and injection molded five different bio-composites. In their study, five types of polymer matrices (Ecoflex, polylactic acid, Ecovio, Bioflex, Tenite Propionate) with only wood flour were used as a reinforcement. A Battenfeld HM 60/210 IM machine had been used for preparing the

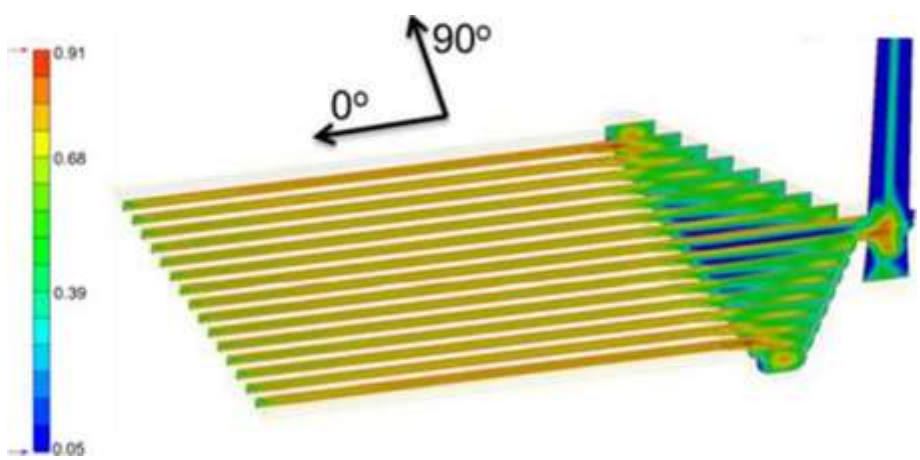

Fig. 13 Design of the film-gated mold used for injecting plate samples with dimensions of 70 mm × 70 mm × 1.5 mm. The color coding indicates the fiber orientation, and the scale bar shows the orientation factor (as obtained by Moldex 3D simulation for fiber glass fiber composites). The mold design was chosen so as to obtain a uniform orientation throughout the mold area (adapted from Ansari et al., 2017)

composites. Pickering and Beg (Beg & Pickering, 2006) investigated the effect of pretreatment on wood-polypropylene composite. Granulated and dried extruded compounded pellets were injection molded by using a BOY15-S IM machine. Jayaraman and Bhattacharyya (Jayaraman & Bhattacharyya, 2004) evaluated the mechanical characteristics of wood fiber/wasted polyethylene composites. A Ray-Ran laboratory IM machine was used for molding the test specimen. Mohanty and Singh (Singh & Mohanty, 2007) fabricated wood/ bacterial bio-plastic composite and evaluated its performance. Before extrusion, both maple wood fiber and polyhydroxybutyrate-co-valerate (PHBV) were dried. Then, the materials were passed through a micro-extruder before being fed into a pre-heated mini-IM machine for fabricating sample. They varied the retention time (ranges from 3 to 10 s) based on the proportion (wt%) of the reinforcement (ranges from 0 to 40%) and matrix (ranges from 100 to 60%) content in the mixture. The processing temperature was 160 °C. The resistance to natural weathering and biodegradability of wood flour/PP composite has been assessed by Vedrtnam et al. (Vedrtnam et al., 2019). The JSW 18OH IM machine was used to prepare the specimens. It is found that exposure of products to UVB radiation deteriorated the matrix quality, results in inferior mechanical properties. Glass fiber and carbon fiber can be used as filler materials in wood fiber/PP products to prepare the hybrid composites (Guo & Kethineni, 2020). Engel E-victory 30, the injection-molding machine used for making all the specimens, consists of a hydraulic clamping unit and an electric injection unit. Andrzejewski et al. (Andrzejewski et al., 2019) conducted the feasibility study to use a cork-wood hybrid filler system in PP/PLA-based com- posites to improve the mechanical properties. The wood flour type used during this study was Lignocel C120, the particle size ranges 70-150 μm. The test samples were fabricated using Engel ES80/20HLS IM machine after blending in ZAMAK EH-16.2D.

Coir fiber based

Coir materials can be used as reinforcement with different thermoplastic, thermosetting, and cement-based bio-composites to improve the mechanical properties (Hasan et al., 2021). The chemical treatment of coir fiber by maleic anhydride grafted to polylactic acid (MAPLA) and poly methyl vinyl ether-alt-maleic anhydride (MA-c-PMVE) improves the mechanical properties of coir fiber/PLA bio-composites (González-López et al., 2019). The materials were first processed in a Micro 27 32D twin-screw extruder. The pellets were injection molded in an ES-1000 IM machine. The mold filling phase behavior controls the final part structure. The flow behavior can be predicted using the incompressible Navier-Stokes equation (SemlaliAouraghHassani et al., 2019). Experimental work has been done for short coir fiber/PP composites to verify the mathematical model. Engel e-victory IM machine was used to prepare the final products. Gunturu et al. (Gunturu et al., 2020) characterized the banana/coir/PP hybrid composites (Gunturu et al., 2020). The pellets were fabricated by using a twin-screw extruder, whereas the specimens were manufactured by ARBURG 500-210 50 ton IM machine. Coir fiber can be used as the reinforcement in PHB (polyhydroxybutyrate) (da Silva Moura et al., 2019). It is found from the injection molded final products that the presence of the treated fiber in the PHB matrix improved thermal stability along with better interfacial adhesion.

Miscellaneous natural fiber composites

Junkasem et al. (2006) studied the mechanical characteristics of roselle/polypropylene composite. MAPP was added with polypropylene and roselle fiber, and the mixtures were transferred into a self-wiping co-rotating twin-screw extruder for compounding. After that, the dried pellets were fed into ARBURG Allrounder® 270 M IM machine for fabricating the test specimen. Xu et al. (2012) fabricated ramie fibers reinforced PLA composite and examined fibers' alignment and nucleation activity in the composite. Abu-Sharkh & Hamid (2004) analyzed the thermal and mechanical characteristics of date palm fiber/polypropylene composites. They also examined the degradability of the composite in spontaneous and artificial weather. AnES 80/25 type IM machine has been used for composite manufacturing. Zhang et al. (2012) assessed the thermal and mechanical characteristics of basalt/PBS composites. Dried basalt fibers and PBS granules were compounded in the twin-screw extruder. The compounded materials were again cut to the granules and transferred to the DH-90 IM machine for sample fabrication. Basalt fiber can be compounded with PP and glass fiber. A TI-30F6 IM machine was used for hybridization (Yan et al., 2017). It is found that such hybridization enhances the fiber agglomeration phenomenon, results in better mechanical properties. Yu et al. studied the 3D microstructural characterization of short basalt fiber/polyamide 6,6 (PA6,6) composites (Yu et al., 2020). The composite was mixed with a co-rotating, intermeshing twin-screw extruder, and the pellets were feed in HAAKE IM machine. Koffi et al. (2021) was investigated that the injection-molded Birch fiber reinforced HDPE composites offer better performance than those manufactured using other techniques. The specimens were produced using a 100 T Zerus 900 press IM machine. The feasibility of using sustainable biocarbon in fabricating composite materials has been assessed by Abdelwahab et al. (2019). Biocomposites were produced using 30 wt% biocarbon in a PP matrix. Banana fiber provides a better prospect to use as the reinforcement in acrylonitrile butadiene styrene (ABS), high impact polystyrene (HIPS), and high density polyethylene (HDPE) matrix (Kusić et al., 2020). The compounds were obtained by extrusion through LABTECH-LTE 20-40 twin-screw extruder, and the specimens were fabricated Engel e-Max 440/100 IM machine to conduct the mechanical tests. Mohammed et al. (2016) characterized the physicochemical properties of sugar palm-based biocomposites. Thermoplastic polyurethane was considered a matrix in their study, whereas the operating parameters were speed, fiber sizes, and temperatures. Thermo Scientific Eurolab 16 extruder machine was used to fabricate the samples. Improvement of the impact resistance has been studied by Várdai et al. (2021). The PP polymer was compounded with sugar palm using a Brabender twin-screw compounder, whereas the samples were prepared by Demag IntElect 50/330-100 IM machine.

Practical implication

Based on the required mechanical and physical properties, the applications of composites are developing in numerous divisions such as aviation, automobiles, development building materials, human nourishment, sports, and pharmaceutical and fine chemicals (Reddy & Yang, 2005). Osoka et al. (2018) investigated the mechanical properties of empty Plantain Bunch Fiber, empty Palm Bunch Fiber and Rattan Palm Fiber strengthened Polyester, and epoxy resins composites for automobile application. World's leading automobile manufacturers, Mercedez-Benz, Audi, BMW, Toyota, have already taken the initiative to use natural fiber-based composites to fabricate various automobile parts (Puglia et al., 2004; Koronis et al., 2013; Sanjay et al., 2016). Kenaf, flax, jute, sisal, sugarcane, and coir fibers are used in the automobile industry. Nowadays, approximately 50% of components of the airplane are fabricated from composites. Numerous studies have been carried out to investigate the potential application of ramie fiber (Boegler et al., 2015), flax fiber (Black, 2017), cotton fiber (Eloy et al., 2015), etc., in the aerospace sector (Mansor et al., 2019). In the construction sector, wood or timber-based composites can be used to manufacture those components. Coir fiber, jute fiber, rice husk, straw, and their composites are heavily used in manufacturing wall panels, flooring, roofing, etc. (Keya et al., 2019). Natural fiber composites can also fabricate bridge components (Anal & Verma, 2017), beams, columns, building templates, etc. (Bakis et al., 2002). In the chemical sector, various types of reactor, pipe, storage tank, casings, are made using such composites (Gupta et al., 2016). Composite materials have been utilized in orthopedic applications, especially hip joint replacement, bone fixation plates, bone cement, and bone grafts. Cotton, coconut, flax, hemp, sisal, jute, etc., fibers are commonly used in the medical and pharmaceutical sector (Morris et al., 2020; Tavares et al., 2020; Kumar et al., 2020; Sarasini et al., 2015).Sports materials are presently made utilizing composite materials, e.g., tennis boards, badminton, golf clubs, climbing ropes, and various lines, are fabri- cated from natural fiber composites (Wang, 2012). Nat- ural fibers such as bamboo-, flax-, and wood fibers- based composite materials have been used to make sev- eral musical applications (Phillips & Lessard, 2012).

Conclusion

The demand for bio-composites is soaring up significantly as being the most viable alternative of other non-degradable composites. This review article discussed the details of the IM process and associated operations to fabricate natural fiber composites. In this regard, various natural fibers, their compatible polymers, along the compounding details are mentioned. In addition, the manuscript also covers the state-of-the-art regarding IM equipment in composite fabrication. Nowadays, bio-composites have great feasibility in many fields such as automobile, aircraft, and bio-medical, which led to growing more interest in fabricating them. Through literature review, most industry adopts IM for the composite manufacturing. It is because the IM process is both time-efficient and cost-efficient in comparison with other production processes. On top of that, injection- molded products ensure less porosity and high uniform- ity. However, researchers are still working on making more updated IM machines. As far as natural fiber isconcerned, almost all types can be manufactured by the IM technique.

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