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COMPOSTABLE NONWOVEN WITH POLYHYDROXYALKANOATE CONTINUOUS FILAMENTS

Abstract

According to one or more embodiments, a compostable fabric includes a nonwoven fabric that includes continuous filaments with a polymeric composition that is fully biodegradable and includes about 51 weight percent to about 100 weight percent of a polyhydroxyalkanoate. The compostable fabric is biodegradable and demonstrates about 90% to about 100% conversion of organic carbon to carbon dioxide (CO₂) after 180 days as measured by ASTM D 5338 test method.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATION [0001] This application claims the benefit of U.S. Provisional Application No. 63/553,347, filed Feb. 14, 2024, which is incorporated herein in its entirety by reference.

BACKGROUND

[0002] The present disclosure relates to nonwovens, and more particularly, to compostable nonwovens with polyhydroxyalkanoate (PHA) continuous filaments.

[0003] Non-biodegradable plastics are not broken down by biological actions. Therefore, non-biodegradable plastic waste build up is a persistent environmental challenge. For example, non-biodegradable plastic build-up in aquatic systems leads to increased maintenance costs.

[0004] On the other hand, biodegradable plastics may be physically broken down by biological action, such as by naturally occurring microorganisms, into biogases like carbon dioxide and methane, biomass, and water. Such biodegradable plastics are therefore a more desirable choice for materials that may end up in wastewater.

[0005] Compostability refers to a material's ability to be satisfactorily composted, at rates comparable to known compostable materials, in municipal and industrial aerobic composting facilities. ASTM D6400 test method is a standard specification for compostability and measures biodegradability, disintegration, and lack of ecotoxicity. The International Biodegradable Products Institute will issue a logo for compostability once a product is verified to meet ASTM D6400 specifications. Unfortunately, most plastic materials, especially fossil fuel-based polymers, and particularly those used to make woven and nonwoven fabrics, do not meet such standards and are therefore not compostable according to ASTM D6400.

SUMMARY

[0006] According to one or more embodiments, a compostable fabric includes a nonwoven fabric that includes continuous filaments with a polymeric composition that is fully biodegradable and includes about 51 weight percent to about 100 weight percent of a polyhydroxyalkanoate. The compostable fabric is biodegradable and demonstrates about 90% to about 100% conversion of organic carbon to carbon dioxide (CO₂) after 180 days as measured by ASTM D5338 test method.

[0007] According to other embodiments, a method of making a compostable fabric includes extruding a polymeric composition to form continuous filaments. The polymeric composition is fully biodegradable and includes about 51 weight percent to about 100 weight percent of a polyhydroxyalkanoate. The method further includes entangling the continuous filaments to form a nonwoven fabric.

[0008] Additional features and advantages are realized through the techniques of the present invention. Other embodiments and aspects of the invention are described in detail herein and are considered a part of the claimed invention. For a better understanding of the invention with the advantages and the features, refer to the description and to the drawings.

Description

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0009] For a more complete understanding of this disclosure, reference is now made to the following brief description, taken in connection with the accompanying drawings and detailed description, wherein like reference numerals represent like parts:

[0010] FIG. 1 is schematic of a method of making a nonwoven fabric;
 [0011] FIG. 2A is an image of a nonwoven fabric before hydroentangling;
 [0012] FIGS. 2B and 2C are high magnification views of the continuous filaments in FIG. 2A;
 [0013] FIG. 3A is an image of a nonwoven fabric before hydroentangling;
 [0014] FIGS. 3B and 3C are high magnification views of the continuous filaments in FIG. 3A;
 [0015] FIG. 4A is an image of a nonwoven fabric before hydroentangling;
 [0016] FIGS. 4B and 4C are high magnification views of the continuous filaments in the nonwoven of FIG. 4A after hydroentangling;
 [0017] FIG. 5 is a graph showing tenacity of PHA continuous filaments as a function of percent elongation;
 [0018] FIG. 6A is an image of a nonwoven fabric after hydroentangling;
 [0019] FIGS. 6B and 6C are high magnification views of the filaments in the nonwoven fabric of FIG. 6A;
 [0020] FIG. 7 is a graph showing average cumulative carbon dioxide (CO₂) for all samples at 179 days;
 [0021] FIG. 8 is a graph showing absolute biodegradation percentages at 179 days;
 [0022] FIG. 9 is a graph showing average biodegradation relative to a positive control (cellulose) for all samples at 179 days;
 [0023] FIG. 10A is a photo of a blank sample taken on day 48 of testing;
 [0024] FIG. 10B is a photo of a polypropylene sample taken on day 48 of testing;
 [0025] FIG. 10C is a photo of polyhydroxyalkanoate (PHA) sample taken on day 48 of testing;
 [0026] FIG. 10D is a photo of a blank sample taken on day 76 of testing;
 [0027] FIG. 10E is a photo of a polypropylene sample taken on day 76 of testing; and
 [0028] FIG. 10F is a photo of polyhydroxyalkanoate (PHA) sample taken on day 76 of testing.

DETAILED DESCRIPTION

[0029] Polylactic acid (PLA) is a plastic polymer material that is partially biodegradable under limited conditions, and in particular, only breaks down under commercial operation conditions associated with high heat and moisture content, for example, at temperatures of 50 degrees Celsius and higher and moisture contents of greater than 85%. Other than these specific conditions, PLA is otherwise environmentally stable under normal terrestrial and aquatic environments. Further, PLA is not fully compostable, in accordance with industry standard ASTM D6400 test method.

[0030] Polyhydroxyalkanoates (PHAs), also known as poly(3-hydroxyalkanoates) are biobased polyesters synthesized by strains of natural bacteria. The bacteria synthesize PHAs as nutrient reserves when their growth is limited by various stressors. PHAs can be harvested from the bacteria to produce compostable plastics. An advantage of PHA is that microorganisms in natural environments secrete extracellular enzymes to fully biodegrade the polyesters. Thus, PHAs are both synthesized and metabolized under natural conditions that do not require commercial operations under high heat and/or moisture, in direct contrast to PLA. PHA is therefore an advantageous polymer for use in a variety of applications, such as agricultural applications.

[0031] Despite the attractiveness of PHA materials, forming strong polymer filaments that can be used to make nonwoven fabrics presents challenges. In particular, making continuous filaments that can be used to make a spunbond nonwoven is challenging for several reasons. First, the filaments are fragile and sensitive to processing conditions, such as temperature, drawing pressure, water entangling pressure, and line speed. Filaments are particularly sensitive during unwinding and tend to swell, which results in significant breakage. Second, selecting and employing the appropriate type (e.g., molecular weight) and blend of PHA to afford strong enough filaments is challenging. Further, defining filament and processing parameters are critical to making a compostable nonwoven with continuous filaments with PHA. To date, polymer blends that include PHA require other polymers, such as PLA, to increase strength of the fibers to withstand processing parameters. However, as discussed above, such blends are not fully biodegradable or compostable and therefore

not suitable for many nonwoven applications.

[0032] Turning now to an overview of technologies that are more specifically relevant to aspects of the invention, described herein is are fully biodegradable and compostable fabrics that are nonwoven fabrics of continuous filaments made from a polymeric composition that is fully biodegradable and includes about 51 weight percent (wt. %) to about 100 wt. % of a polyhydroxyalkanoate (PHA), wherein the fabric fully degrades by at least 90% conversion of organic carbon to carbon dioxide (CO₂) and water after 180 at 58 degrees Celsius (° C.) days as measured by ASTM D 5338 test method.

Polymeric Compositions

[0033] The continuous filaments are made from a polymeric composition. In some embodiments, the polymeric composition includes 100% PHA (i.e., one or more PHAs). The PHA in the polymeric composition is one or more copolymers or blends of PHAs. Non-limiting examples of PHAs include poly(3-hydroxybutyrate) (PHB), polyhydroxyvalerate (PHV), polyhydroxyhexanoate (PHH), or any combination thereof. The PHA is a copolymer or mixture of one or more of poly(3-hydroxybutyrate) (PHB), polyhydroxyvalerate (PHV), and polyhydroxyhexanoate (PHH) in some embodiments. In embodiments, the PHA includes a copolymer of hydroxybutyrate and hydroxyhexanoate. In other embodiments, the PHA is a copolymer that includes about 75 to about 99 mole percent hydroxybutyrate and about 1 to about 25 mole percent hydroxyhexanoate. In other embodiments, the PHA includes a copolymer of hydroxybutyrate and hydroxyhexanoate. Yet in other embodiments, the PHA is a copolymer that includes about 85 to about 95 mole percent hydroxybutyrate and about 5 to about 15 mole percent hydroxyhexanoate.

[0034] In some embodiments, the nonwoven fabric includes continuous filaments made from a polymeric composition that is fully biodegradable and includes about 51 wt. % to about 100 wt. % of a polyhydroxyalkanoate. In other embodiments, the polymeric composition includes about 60 wt. % to about 90 wt. % of a polyhydroxyalkanoate. Still yet, in other embodiments, the polymeric composition includes about or any range between about 51, 55, 60, 65, 70, 75, 80, 85, 90, 95, and about 100 wt. % of a polyhydroxyalkanoate. In one or more embodiments, the polymeric composition includes 100% polyhydroxyalkanoate, and the continuous filaments used to make the nonwoven are only polyhydroxyalkanoate (e.g., free of/0% other polymers).

[0035] The initial resin molecular weight of the PHA is critical to ensure that the continuous filament fibers are strong enough to withstand the process parameters, including temperature and pressure, and do not degrade. In some embodiments, the PHA has a molecular weight of about 50,000 Daltons to about 2.5 million Daltons. In other embodiments, the PHA has a molecular weight of about 150,000 Daltons to about 600,000 Daltons. Still yet, in other embodiments, the PHA has a molecular weight of about 150,000 Daltons to about 500,000 Daltons. In some embodiments, the PHA has a molecular weight about or in any range between about 50,000 Daltons, 100,000 Daltons, 200,000 Daltons, 300,000 Daltons, 400,000 Daltons, 500,000 Daltons, 600,000 Daltons, 700,000 Daltons, 800,000 Daltons, 900,000 Daltons, 1.0 million Daltons, 1.1 million Daltons, 1.2 million Daltons, 1.3 million Daltons, 1.4 million Daltons, 1.5 million Daltons, 1.6 million Daltons, 1.7 million Daltons, 1.8 million Daltons, 1.9 million Daltons, 2.0 million Daltons, 2.1 million Daltons, 2.2 million Daltons, 2.3 million Daltons, 2.4 million Daltons, and about 2.5 million Daltons.

[0036] In some embodiments the PHA has a density of about 1.00 to about 1.65 grams per cubic centimeter (g/cm³). In other embodiments, the PHA has a density of about 1.10 to about 1.40 g/cm³. In some embodiments, the PHA has a density of about 1.24 g/cm³. Still yet, in other embodiments, the PHA has a density about or in any range between about 1.00, 1.02, 1.04, 1.05, 1.06, 1.08, 1.10, 1.12, 1.14, 1.15, 1.16, 1.18, 1.20, 1.22, 1.24, 1.25, 1.26, 1.28, 1.30, 1.32, 1.34, 1.35, 1.36, 1.38, 1.40, 1.42, 1.44, 1.45, 1.46, 1.48, 1.50, 1.52, 1.54, 1.55, 1.56, 1.58, 1.60, 1.62, 1.64, and 1.65 g/cm³.

[0037] In embodiments, the polymeric composition includes PHA and one or more polymers to provide a nonwoven that is fully compostable under standard industry conditions and definitions (as defined below). In some embodiments, the polymeric composition further includes polylactic acid, a polycaprolactone, a polybutylene succinate, a polybutylene succinate adipate, a polybutylene adipate terephthalate, a starch, or any combination thereof.

[0038] The polymeric composition includes other components in one or more embodiments. In some embodiments, the polymeric composition includes a pigment, carbon black, graphene, a flame retardant, a filler, an impact modifier, an antioxidant, an ultraviolet (UV) stabilizer, or any combination thereof.

[0039] The filler is a material that increases the solid content and can serve as a thickener. When present, the filler is in the polymeric composition in an amount of about 0.1 percent to about 50 percent by weight of the polymeric composition. In some embodiments, the filler is in the polymeric composition in an amount of about or in any range between about 0.1%, 1%, 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, and about 50%.

[0040] Non-limiting examples of fillers include graphene, calcium carbonate, talc, nano clays, nanocellulose, hemp fibers, kaolin, carbon black, wollastonite, glass fibers, carbon fibers, graphite fibers, mica, silica, dolomite, barium sulfate, magnetite, halloysite, zinc oxide, titanium dioxide, montmorillonite, feldspar, asbestos, boron, steel, carbon nanotubes, cellulose fibers, flax, cotton, starch, polysaccharides, aluminum hydroxide, magnesium hydroxide, modified starches, chitins and chitosans, alginates, gluten, zein, casein, collagen, gelatin, polysaccharides, guar gum, xanthan gum, succinoglycan, natural rubbers, rosinic acid, lignins, natural fibers, jute, kenaf, hemp, ground nut shells, wood flour, or any combination thereof.

[0041] When present, the impact modifier is present in the polymeric composition in an amount of about 0.1 percent to about 20 percent by weight of the polymeric composition. In some embodiments, the impact modifier is in the polymeric composition in an amount of about or in any range between about 0.1%, 1%, 2%, 3%, 4%, 5%, 6%, 7%, 8%, 9%, 10%, 11%, 12%, 13%, 14%, 15%, 16%, 17%, 18%, 19%, and about 20%.

[0042] Non-limiting examples of the impact modifier include acrylic-based resins and emulsions, isosorbide derivatives, natural rubbers, aliphatic polyesters, or mixtures thereof.

[0043] UV light stabilizers are chemical compounds that mitigate polymer deterioration due to photodamage. When present, the UV light stabilizer is present in an amount of about 0.1 to about 0.85 percent (%) by weight of the polymeric composition. In other embodiments, the UV light stabilizer is present in an amount about or in any range between 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, and 0.85% by weight of the polymeric composition.

[0044] Non-limiting examples of UV light stabilizers include hindered amine light stabilizers (HALS) (e.g., tetramethylpiperidine compounds), as well as some antioxidants and free radical scavengers.

[0045] Antioxidants are chemical compounds that inhibit autoxidation of polymers when exposed to oxygen, and more typically in the presence of oxygen and heat. When present, the antioxidant is present in an amount of about 0.1% to 0.25% by weight of the polymeric composition. In other embodiments, the antioxidant is present in an amount about or in any range between 0.06, 0.1, 0.12, 0.20, and 0.25% by weight of the polymeric composition.

[0046] Non-limiting examples of antioxidants include phenolic antioxidants, phosphite antioxidants, phosphonite antioxidants, or any combination thereof.

Filaments

[0047] The filaments used to make the nonwovens are continuous filament yarns, also referred to as continuous filaments, and continuous yarns. A “continuous filament” is extruded as a single, continuous strand of filament. The continuous filament is entangled together to form the nonwoven.

[0048] The continuous filaments are formed by extruding and drawing the polymeric composition

with the PHA. The polymeric composition is highly shear dependent reflecting premature degradation, and modified by reducing shear rates and die temperatures to ensure a sufficient working temperature for fiber melt extrusion temperatures as described below. The PHA in the polymeric composition is shear and temperature sensitive, which means that the dwell time in the extruder at elevated temperatures can cause excessive molecular weight degradation. Thus, the PHA in the polymeric composition is selected to have a medium chain length PHA, which is required for fiber melt extrusion process conditions. Without such modification of the polymeric composition, there is not sufficient melt strength to form and draw the fiber or provide tenacity to form a functional material post extrusion.

[0049] The continuous filaments of the nonwoven fabric have an average diameter of about 10 to about 100 microns/micrometers. In some embodiments, the continuous filaments have an average diameter of about 30 to about 70 microns. Still yet, in embodiments, the continuous filaments have an average diameter about or in any range between about 10, 20, 30, 40, 50, 60, 70, 80, 90, or 100 microns.

[0050] The continuous filaments are a homogeneous blend and admixture of PHA and other non-fossil fuel bio-based polymers and/or copolymers and additives creating a homogeneous melt-blendable mixture of one or more PHA polymers and/or copolymers. The admixture is designed to degrade over time, as demonstrated by degradation testing, unlike traditional fossil based polymers.

Process

[0051] The nonwoven fabric is fabricated by spunbonding, hydroentangling, needlepunching, thermal bonding, point bonding, or a combination thereof. To produce the filaments, the raw materials are mixed, and filaments are formed in spinnerets. The filaments pass through an extruder where they are heated under shear. The shearing in the presence of heat will result in a homogeneous melt with proper selection of the composition. A collection of filaments is combined together to form the nonwoven web.

[0052] FIG. 1 is a schematic diagram of a method of making nonwovens according to embodiments. The raw materials **101** forming the polymeric composition, including PHA and optionally one or more polymers and/or additives, are combined and mixed. The components are mixed and pass through dosing equipment with a suction device **102**. The mixed components enter the extruder **103**, which heats to melt the polymers in the polymeric composition.

[0053] The filaments/fibers are formed/extruded by the process of melt spinning. In melt spinning, there is no mass loss in the extrudate. Melt spinning is differentiated from other spinning, such as wet or dry spinning from solution, where a solvent is being eliminated by volatilizing or diffusing out of the extrudate resulting in a mass loss.

[0054] The melt spinning (extrusion) temperature is critical because of the delicacy of the PHA and resulting filaments, which are highly temperature sensitive. Melt spinning is performed at temperatures of about 120 degrees to about 200 degrees Celsius, about 130 to about 190 degrees Celsius, or about 140 to about 180 degrees Celsius. In other embodiments, melt spinning is performed at a temperature about or in any range between about 120, 125, 130, 135, 140, 150, 155, 160, 165, 170, 175, 180, 185, 190, 195, and 200 degrees Celsius. The processing temperature is determined by the chemical nature, molecular weights, and concentration of each component.

[0055] Fiber spinning speeds of greater than 100 meters/minute are required. In embodiments, the fiber spinning speed is from about 1,500- to about 5,000 meters/minute, about 1,500 to about 2,000 meters/minute, or about 1,750 to about 2,250 meters/minute. In some embodiments, the fibers spinning speed is about or in any range between about 1,500; 1,750, 2,000; 2,250; 2,500; 2,750; 3,000; 3,250; 3,500, 4,000; 4,500; and 5,000 meters/minute.

[0056] Continuous fibers are produced through spunbond methods or meltblowing processes, or non-continuous (staple) fibers can be produced. The various methods of fiber manufacturing can also be combined to produce a combination technique.

[0057] The filaments are stretched by spunbond stretching. A melt spin pump slows into the

spinnerets. The filaments expelled through the spinneret plate are drawn/stretched and cooled in drawing equipment **104**, which includes quench air ducts that supply air to cool the filaments from the spinneret. The filaments are stretched into long, thin filaments once cooled. The filaments are separated into bundles of a plurality of filaments.

[0058] The foregoing spunbond stretching is distinguished from meltblown stretching, which uses high speed airflow to rapidly stretch the polymer melt into filaments. The resulting fibers from meltblown stretching are short and thin.

[0059] The filaments **105** are laid on a web forming belt **106**, which is coupled to a drive system and suction channel. The web is then mechanically bonded. The web is bonded by entangling the filaments by hydroentangling using high pressure jets **107** of water to penetrate the web, hit the web forming belt **106**, and bounce back, causing the filaments to mechanically entangle.

[0060] In embodiments in which entangling is hydroentangling, the water pressure jets employ a water pressure of about 50 to about 300 Bars, about 75 to about 275 Bars, or about 100 to about 200 Bars. In other embodiments, the water pressure jets employ a water pressure about or in any range between about 50, 75, 100, 125, 150, 175, 200, 225, 250, 275, and 300 Bars.

[0061] In other embodiments, entangling is by needlepunching (not shown).

[0062] The entangled web passes through a dryer **108** to remove excess water and wound onto a roll using a winding machine **109**.

[0063] The continuous filaments are used to make nonwoven webs/fabrics, among other suitable articles. The fibers are converted to nonwovens by different bonding methods. Continuous fibers can be formed into a web using spunbond type technologies, while staple fibers can be formed into a web using carding, airlaid, or wetlaid technologies. Typical bonding methods include: calendar (pressure and heat), thru-air heat, mechanical entanglement, hydrodynamic entanglement (hydroentangling), needle punching, and chemical bonding and/or resin bonding. Thermally bondable fibers are required for the pressurized heat and thru-air heat bonding methods.

[0064] In one or more embodiments, a method of making a compostable fabric includes extruding a polymeric composition to form continuous filaments. The polymeric composition is fully biodegradable and includes about 51 weight percent to about 100 weight percent of a polyhydroxyalkanoate (PHA). The method further includes entangling the continuous filaments to form a nonwoven fabric.

Nonwoven Properties

[0065] The fabrics are biodegradable, fully consumer compostable, and 100% biodegradable under natural terrestrial and aquatic conditions. While many alleged biodegradable polymers, such as polylactic acid (PLA) polymers and copolymers, only break down and compost in commercial operations associated with high heat and moisture content, the nonwovens described herein are fully biodegradable and consumer compostable under natural terrestrial and aquatic conditions.

[0066] In some embodiments, the fabrics described herein do not include PLA or include 0% PLA. In other embodiments, the fabrics described herein include 0% to about 10% PLA, or about or in any range between about 0%, 1%, 2%, 3%, 4%, 5%, 6%, 7%, 8%, 9%, and 10% PLA.

[0067] Being biodegradable means that when the nonwoven is exposed to an aerobic and/or anaerobic environment, the ultimate fate is reduction to monomeric components due to microbial, hydrolytic, and/or chemical actions. Under aerobic conditions, biodegradation leads to the transformation of the polymer into carbon dioxide and water. Under anaerobic conditions, biodegradation leads to the transformation of the materials into carbon dioxide, water, and methane. The American Society for Testing and Materials (ASTM) D5338 test method (Standard Test Method for Determining Biodegradation of Plastic Materials Under Controlled Composting Conditions, Incorporating Thermophilic Temperatures) provides steps to measure the percent of test material that mineralizes as a function of time by monitoring the percentage of carbon dioxide (CO₂) being released and converted from organic carbon as a result of assimilation by microorganisms in the presence of active compost held at a thermophilic temperature of 58 degrees

Celsius. The carbon dioxide production testing is conducted via electrolytic respirometry. The definitions set forth in ASTM D6400, Standard Specification for Labeling of Plastics Designed to be Composted in Municipal or Industrial Facilities, are used alongside ASTM D5338.

[0068] As used herein, in some embodiments, the term “biodegradable” means about 90% to about 100% of organic carbon in the nonwoven is converted to carbon dioxide (CO.sub.2) and water after 180 days as measured by ASTM D 5338 test method. In other embodiments, the term “biodegradable” means about or in any range between about 90%, 91%, 92%, 93%, 94%, 95%, 96%, 97%, 98%, 99%, and about 100% of organic carbon in the nonwoven is converted to carbon dioxide (CO.sub.2) and water after 180 days as measured by ASTM D 5338 test method.

[0069] In some embodiments, the nonwoven fabric demonstrates about 90% to about 100% conversion of organic carbon to carbon dioxide (CO.sub.2) after 162 days in the absolute as measured by ASTM D 5338 test method. In other embodiments, the nonwoven fabric demonstrates about or in any range between about 90%, 91%, 92%, 93%, 94%, 95%, 96%, 97%, 98%, 99%, and about 100% of organic carbon is converted to carbon dioxide (CO.sub.2) and water after 162 days in the absolute as measured by ASTM D 5338 test method.

[0070] In some embodiments, the nonwoven fabric demonstrates about 90% to about 100% conversion of organic carbon to carbon dioxide (CO.sub.2) after 143 days as compared to a cellulosic control as measured by ASTM D 5338 test method. In other embodiments, the nonwoven fabric demonstrates about or in any range between about 90%, 91%, 92%, 93%, 94%, 95%, 96%, 97%, 98%, 99%, and about 100% of organic carbon is converted to carbon dioxide (CO.sub.2) and water after 143 days as compared to a cellulosic control as measured by ASTM D 5338 test method.

[0071] The nonwovens described herein are “compostable” and therefore can be used in consumer compostable condition where soil and moisture are the initiators to mineralize the nonwoven material. The nonwovens described herein are also consumer compostable. Compostability refers to a material's ability to be satisfactorily composted, at rates comparable to known compostable materials, in municipal and industrial aerobic composting facilities. ASTM 6400 test method is a standard specification for compostability and measures biodegradability, disintegration, and lack of ecotoxicity. The International Biodegradable Products Institute will issue a certification for compostability once a product is verified to meet ASTM 6400 specifications. The nonwovens described herein meet such specifications and are deemed “compostable.” The test to measure biodegradability is described above. To meet the biodegradability criteria for compostability, the material must achieve at least about 60 percent conversion to carbon dioxide within 40 days. For the disintegration criteria, the material must have less than 10 percent of the test material remain on a 2 millimeter screen in the actual shape and thickness that it would have been in the disposed product. To determine lack of ecotoxicity, the biodegradation byproducts must not exhibit a negative impact on seed germination and plant growth, as measured by OECD 208 test method. Accordingly, the nonwovens described herein are certified “compostable,” which means that they achieve at least 60 percent conversion to carbon dioxide within 40 days, have less than 10 percent of material remain on a 2 millimeter screen in the actual shape and thickness that it would have been in the disposed product, and do not exhibit a negative impact on seed germination and plant growth.

[0072] As used herein, in some embodiments, the term “compostable” means the nonwoven fabric is compostable in industrial aerobic facilities by demonstrating the following properties, as set forth in ASTM D6400: (1) disintegration wherein about 0% to about 10% of the compostable fabric's original dry weight remains after sieving on a 2.0 millimeter sieve after 84 days in a controlled composting test as measured in accordance with ISO 16929 with a minimum vessel volume of 35 Liters, or ISO 20200 under thermophilic aerobic composting conditions; (2) concentrations of regulated metals less than 50% of those prescribed for sludges or composts in a country where the compostable fabric is sold; and (3) a germination rate and a plant biomass of the compostable fabric composts shall be at least 90% that of corresponding blank composts for two different plant

species following OECD Guideline 208 with the modifications found in Annex E of EN 13432. [0073] As mentioned above, the nonwovens described herein also disintegrate. Disintegration occurs when the fibrous substrate has the ability to rapidly fragment and break down into fractions small enough not to be distinguishable after screening when composted or to cause drainpipe clogging when flushed. ISO 20200 test method for disintegratability measures the weight loss of test materials over time when exposed to various matrices under thermophilic conditions. Both aerobic and anaerobic disintegration tests are used. Weight loss is determined by the amount of fibrous test material that is no longer collected on an 18 mesh sieve with 1 millimeter openings after the materials is exposed to wastewater and sludge. For disintegration, the difference in the weight of the initial sample and the dried weight of the sample recovered on a screen will determine the rate and extent of disintegration. The nonwovens herein disintegrate, which means that they have less than 10% of the test material remain on a 2 millimeter screen in the actual shape and thickness that it would have been in the disposed product, as measured by ISO 20200 test method in some embodiments.

[0074] In some embodiments, the nonwoven fabrics are compostable and demonstrate a rate of disintegration, as set forth in ASTM D6400, wherein about 0% to about 10% of the compostable fabric's original dry weight remains after sieving on a 2.0 millimeter sieve after 84 days in a controlled composting test as measured in accordance with ISO 16929 with a minimum vessel volume of 35 Liters, or ISO 20200 under thermophilic aerobic composting conditions. In other embodiments, the nonwoven fabrics are compostable and demonstrate a rate of disintegration, as set forth in ASTM D6400, wherein about or any range between about 0%, 1%, 2%, 3%, 4%, 5%, 6%, 7%, 8%, 9%, and about 10% of the compostable fabric's original dry weight remains after sieving on a 2.0 millimeter sieve after 84 days in a controlled composting test as measured in accordance with ISO 16929 with a minimum vessel volume of 35 Liters, or ISO 20200 under thermophilic aerobic composting conditions.

[0075] In some embodiments, the nonwoven fabrics are compostable and demonstrate concentrations of regulated metals, as set forth in ASTM D6400, of about 0% to about 50% of those prescribed for sludges or composts in a country where the compostable fabric is sold. For example, in the United States, the regulated metal concentrations are found in Table 3 of 40 CFR Part 503.13. In Canada, the regulated metals concentrations are found in Table II of the Trade Memorandum T-4-93. In other embodiments, the nonwoven fabrics are compostable and demonstrate concentrations of regulated metals, as set forth in ASTM D6400, of about or in any range between about 0%, 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, and about 50% of those prescribed for sludges or composts in a country where the compostable fabric is sold.

[0076] In some embodiments, the nonwoven fabrics are compostable and demonstrate a germination rate and a plant biomass of the nonwoven fabric are, as set forth in ASTM D6400, about 90% to about 100% that of corresponding blank composts for two different plant species following OECD Guideline 208 with the modifications found in Annex E of EN 13432. In other embodiments, the nonwoven fabrics are compostable and demonstrate a germination rate and a plant biomass of the nonwoven fabric are, as set forth in ASTM D6400, about or in any range between about 90%, 91%, 92%, 93%, 94%, 95%, 96%, 97%, 98%, and about 100% that of corresponding blank composts for two different plant species following OECD Guideline 208 with the modifications found in Annex E of EN 13432.

[0077] In some embodiments, the compostable fabrics are agricultural fabrics used in agricultural applications, such as to grow mushrooms or cover sugar beets. In other embodiments, the compostable fabrics are used in terrestrial applications or aquatic applications. In some embodiments, the compostable fabrics are used in food service applications.

[0078] The nonwoven fabric has a basis weight of about 20 to about 1,000 grams/square meter (gsm). In some embodiments, the nonwoven fabric has a basis weight of about 100 to about 400 gsm. Still yet, in embodiments, nonwoven fabric has a basis weight about or in any range between

about 20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 220, 240, 260, 280, 300, 320, 340, 360, 380, 400, 420, 440, 460, 480, 500, 520, 540, 560, 580, 600, 620, 640, 660, 680, 700, 720, 740, 760, 780, 800, 820, 840, 860, 880, 900, 920, 940, 960, 980, and 1,000 gsm.

EXAMPLES

Example 1. Continuous Filaments

[0079] A 100% bio-based polymeric composition was extruded to form continuous filaments that were spunbond and hydroentangled into a nonwoven. The bio-based polymeric composition included at least 50% PHA, with the remaining bio-based polymers being non-fossil fuel based polymers. The process parameters are shown in Table 1.

TABLE-US-00001 TABLE 1 Process parameters Drawing pressure 1 bar Pre-entanglement 180 bar Main entanglement 380 bar Line speed 5 m/min

[0080] FIG. 2A shows the fabric before hydroentangling, and FIGS. 2B and 2C show the filaments in the fabric at high magnification. FIG. 3A shows the fabric after hydroentangling, and FIGS. 3B and 3C show the filaments in the fabric at high magnification.

[0081] As shown, the filaments were sensitive during unwinding and tended to “swell,” despite forming a web. During hydroentangling, many fibers were broken, but the web structure was acceptable (FIG. 3C compared to FIG. 2C). The results demonstrated that forming a PHA spunbond nonwoven with hydroentanglement is possible, but the filaments are brittle as expected. Reduced water jet pressure and an adapted creel may improve the process.

Example 2. Nonwovens

[0082] A 100% bio-based polymeric composition (like in Example 1) 100% was extruded to form continuous filaments that were spunbond and hydroentangled into a nonwoven. The optimized process parameters are shown in Table 2. Instead of a main entanglement pressure of 380 bar as in Example 1, a reduced pressure of 180 bar was used.

TABLE-US-00002 TABLE 2 Process parameters Drawing pressure 1 bar Pre-entanglement 180 bar Main entanglement 180 bar Line speed 5 m/min

[0083] Fabric physical properties, including weight (grams per square meters), machine direction (MD) and cross-machine direction (CD) tensile (Newtons per gram), and MD and CD elongation (percent) were measured and compared to a reference 100% polypropylene spunbond hydroentangled nonwoven (Table 3).

TABLE-US-00003 TABLE 3 Nonwoven properties PHA fabric PP fabric Weight (g/m.sup.2) 100 — MD tensile (N/g) 7.75 12 CD tensile (N/g) 4.62 7.8 MD elongation (%) 48 92 CD elongation (%) 60 118

[0084] FIG. 4A shows the fabric before hydroentangling, and FIGS. 4B and 4C show the filaments in the fabric at high magnification. The optimized unwinding and use of the supporting net allowed for production of several meters of the nonwoven. The reduced water pressure also resulted in significantly fewer filament breaks (compare FIGS. 4C and 3C. It was possible to form and entangle a PHA nonwoven. The mechanical performance was lower than the PP nonwoven, which was likely due to the higher density of PHA.

Example 3. Continuous Filaments and Nonwoven Properties

[0085] The extrusion temperatures for 100% PHA were adjusted. A temperature gradient profile of 180, 180, 185, 190, 195, and 195 degrees Celsius was used. However, once the polymer was spinning, it was evident that the temperature was still too high because the spinning stability was very low. The pressure after the filter was reduced from 140 to 65 bars to reduce shearing. Changing the air-cooling temperature and volume did not have a significant impact on stability. Ultimately, the following extrusion temperatures were achieved: 198, 186, 185, 190, 195, and 207 degrees Celsius. The throughput was about 200 kg/h. Any increase in temperature negatively impacted the drawing and resulted in pre-degradation of the polymer matrix

[0086] Table 4 shows the titer, tenacity, and elongation properties of the continuous filaments. FIG. 3 shows the tenacity (cN/dtex) as a function of elongation (%).

TABLE-US-00004 TABLE 4 PHA filament properties Sample Titer (dtex) Tenacity (cN/dtex)

Elongation (%) 1 7.6 1.12 71 2 7.2 1.32 79

[0087] Table 5 shows the properties of the nonwovens. PHA sample 1 and 2 included 100% PHA and were reproduced in duplicate. A PP nonwoven was compared as a control. Despite the temperature limitation of 180 degrees Celsius, the nonwoven was formed. FIG. 6A shows the fabric after hydroentangling, and FIGS. 6B and 6C show the filaments in the fabric at high magnification. TABLE-US-00005 TABLE 5 Nonwoven properties MD tensile MD CD tensile CD Weight ((N/20 cm)/ elongation ((N/20 cm)/ elongation (g/m.sup.2) g) (%) g) (%) PHA 1 209 5.04 56 2.32 55 PHA 2 353 5.62 69 3.38 81 PP — 13 90 7.5 120

Example 4: Compost Inoculum Preparation, Pretesting, and Heavy Metal Analysis

[0088] The following measurements shown in Examples 4-8 were collected in accordance with ASTM D5338, Standard Test Method for Determining Biodegradation of Plastic Materials Under Controlled Composting Conditions, Incorporating Thermophilic Temperatures, and with definitions set forth in ASTM D6400, Standard Specification for Labeling of Plastics Designed to be Composted in Municipal or Industrial Facilities. The methods were only modified to a smaller laboratory scale.

[0089] Compost exhibiting enough biological activity to reach 46° C. was sourced from two separate, local, industrial composting facilities. Both compost samples had spent 2-4 months at either composting plant. The compost was then particle sieved through a 4.76-millimeter (0.187-inch) screen. The two samples of separately sourced compost were then blended in a 75/25 mass-ratio to increase the microbiological diversity and geographical representation of the test inoculum.

[0090] The respiration of the inoculum generated between 50 and 150 milligrams of CO₂ per day per 1 gram of volatile solids over ten days of at 58° C., well within the activity range defined by ASTM D5338 § 9.1. In line with the same standard, the inoculum was found to have an ash content of less than 70%, a pH between 7.0 and 8.2, and a water content between 45% and 50% at the time of pre-testing.

[0091] The inoculum was analyzed for the concentrations of various metals through total acid digestion (Table 6). Zinc and copper levels were above threshold for biological toxicity; however, the inoculum exhibited necessary CO₂ production levels during pre-testing to meet ASTM D5338-15 standards.

TABLE-US-00006 TABLE 6 Heavy metal analysis of compost via total acid digestion Total Acid Digestion ppm (parts per million) Al As B Ca Cd Cr Cu Fe K Mg Lab Sam Alumin. Arsen. Bor. Calc. Cadm. Chrom. Copp. Iron Potass. Magnes. Values smaller than nolimit <20 no no <2 <100 <100 no no no these pose minimal imit limit limit limit limit limit health risk 37264 ACC 16811 3.78 25.24 12178 0.37 21.39 125.96 12660 4960 2508 37265 WH 745 0.21 2.26 2361 <0.01 1.43 4.10 922 880 314 37266 Compost 14700 3.25 25.08 15233 0.18 19.19 101.62 11677 6033 2695 Mix Total Acid Digestion ppm (parts per million) Mn Mo Na Ni P Pb S Zn Lab Sam Mangan. Molybd. Sod. Nick. Phosphor. Lead Sulf. Zinc Values smaller than <3500 <440 no <50 no <75 no <100 these pose minimal limit limit limit health risk 37264 ACC 532.8 3.16 1020 8.59 13830 16.51 3913 322.5 37265 WH 51.3 0.15 113 0.73 630 1.19 192 18.9 37266 Compost 532.9 2.01 1154 7.76 11578 14.84 3413 287.0 Mix

[0092] The compost was 27.04% carbon and 2.49% nitrogen (carbon:nitrogen ratio: 10.8:1). Note that this was a low carbon:nitrogen ratio, but in the acceptable range of 10-40. On average, compost blends sourced from the two local industrial composting facilities in Athens, Georgia typically average around 14 milligrams/kilogram (mg/kg) ammonia, while the compost mix for these experiments was measured at 2,798 mg/kg ammonia, higher than historical averages from these sources. Despite the high ammonia concentrations, the metabolic rate of the inoculum was satisfactory as per ASTM D5338 § 6.3 requirements. The organic carbon and nitrogen were analyzed with an organic elemental analyzer using the combustion method and thermal conductivity detection (TCD). Carbonate salts are highly oxidized, and their carbon content was

not included in organic carbon analysis.

Example 5: Day-0 Analysis and Testing Method

[0093] Due to the high starting pH of the industrial compost (pH 8.4-8.5), the compost was adjusted to a pH of 7.40 using gypsum with 14% weight/weight (w/w) sulfur. To ensure the validity of the study beyond pretesting, the compost inoculum was measured directly prior to testing to have a pH of 7.40, within the acceptable range (7.0-8.2), a total solids (TS) content of 42.44%, total ash content of 24.87%, and a total volatile solids (VS) content of 17.54% (<30% acceptable). The inoculum blank produced between 50-150 mg CO₂/g VS.

[0094] Each test included 6 grams of test material (polypropylene or polyhydroxyalkanoate) or positive control (cellulose) introduced to 250 grams of inoculum prepared in a contained 2.7-liter bioreactor with a refillable water reservoir. The blank control was an exception, which was only 250 grams of inoculum prepared in a bioreactor. The reactors were placed inside of an incubator set to 58° C. All sample and control groups were studied in triplicates to ensure statistical accuracy and reproducibility. All respirometers and hardware are maintained daily. Reactor contents are stirred weekly. All reactors had their moisture content analyzed weekly. Clean, deionized water was added as necessary to a reactor's reservoir or inoculum to keep the moisture of the inoculum between 40-60%. Any abnormal observations or macro-organisms were taken note of and photographed.

Example 6: Sample Moisture Content and Elemental Analysis

[0095] To determine a material's carbon concentration to ensure accurate CO₂ production calculations, a small sample of each material was massed, dried, and re-massed under desiccated conditions (Table 7) to determine the mass-percentage of water for each material. This was performed on day-0 prior to testing to ensure accurate mass-ratios during reactor preparation. In order to determine the mass-percentage of carbon for each test material, a small sample of each test material was dried and subjected to stable isotope ratio analysis (Table 8). Stable isotope ratio analysis was performed by an Elementar, with a limit of detection of less than 0.10%.

TABLE-US-00007 TABLE 7 Moisture content of test materials and positive control for mass calculations, determined with an infrared-drying balance on day-0

Sample	Moisture (%)
Cellulose	3.0
Polypropylene	0.0
PHA	1.1

TABLE-US-00008 TABLE 8 Carbon and nitrogen content of test materials and positive control

Sample	Total Carbon (%)	Total Nitrogen (%)
Cellulose	42.88	0.185
Polypropylene	85.89	0.42
PHA	52.82	0.28

Example 7. Respirometry Evaluation

[0096] The cumulative CO₂ production curves (FIG. 7) were calculated by directly measuring the relative concentration of CO₂ in each individual reactor, taking into consideration the flowrate of each reactor's channel. Each test material and control group represented an average of a triplicate. A test material that underperformed or matched the CO₂ production of the blank would not be considered to be mineralizing into CO₂.

[0097] Absolute biodegradation values (FIG. 8) were determined from the percent of the theoretical mineralized carbon from each sample. Each test material and control group represented an average of a triplicate. All absolute biodegradation percentages were calculated using the rate of CO₂ production of the negative controls (blanks). Per ASTM D5338-15, the positive control (cellulose) must reach 70% biodegradation by day 45 to regard the test as valid.

[0098] Biodegradation was also evaluated by comparison to the positive control (cellulose) (FIG. 9). In the beginning days of the experiments, colonization of all samples and the positive control varied significantly, which was shown by the variability in relative biodegradation values in the first week of testing. Relative biodegradation values represented a comparison of the theoretical CO₂ generated from a sample compared to the CO₂ generated from the positive control (cellulose).

[0099] Cumulative CO₂ production, absolute biodegradation, and relative biodegradation results are shown in Table.

TABLE-US-00009 TABLE 9 179-day averages of cumulative CO₂ production and percent

biodegradation values for each test group Day 179 Absolute Day 179 Relative Cumulative
 Biodegradation Biodegradation Sample CO₂ sub.2 (mg) (%) (%) Polypropylene 26291 ± 355 3.88
 ± 2.26 3.62 ± 2.11 PHA 36429 ± 1801 93.16 ± 15.65 86.79 ± 14.58 Cellulose 35692 ± 2220 107.34
 ± 23.54 N/A Blank 25555 ± 980 N/A N/A

Example 8. Photos of Samples

[0100] Pictures of the blank, polypropylene, and PHA samples on day 48 of testing are shown in FIGS. 10A-C. Pictures of the blank, polypropylene, and PHA samples on day 76 of testing are shown in FIGS. 10D-F.

[0101] The 58° C. positive control (cellulose) reached greater than 70% biodegradation by day 45, as required by ASTM D5338-15 § 13, indicating the validity of the study. All samples integrated uniformly into the compost on the first day of testing. Temperature variation was no more than ±1° C. for either condition.

[0102] Images of the samples illustrate disintegration performance. After the day-76 photographs, the “PHA” samples were no longer visible in the compost inoculum. The “PHA” sample demonstrated a satisfactory rate of biodegradation by achieving more than 90% mineralization by the end of 180 days of testing and satisfying the requirements for a compostable plastic as defined by ASTM D6400 § 6.3. The PHA samples measured >90% absolute biodegradation on day 162 of testing and >90% biodegradation relative to the cellulose control on day 143 of testing.

[0103] The polypropylene, by comparison, returned only 3.88% absolute biodegradation, which was not a significant amount of CO₂ (below 10% of theory carbon mineralization), given the precision of respirometry analysis. Note that no gravimetric disintegration was performed to analyze the sample residual mass.

[0104] Anomalies in the curve shapes for days 76 and 83 were due to a water return issue that led to drying of the inoculum. The curves showed dips in biodegradation that were due to the blank and cellulose controls maintaining moisture control and the two samples becoming too dry for sufficient carbon mineralization. The water return issue were fixed around day 111, and these reactors returned water to the reactors CO₂ normally for the rest of the study.

[0105] According to one or more embodiments, a compostable fabric includes a nonwoven fabric comprising continuous filaments comprising polymeric composition that is fully biodegradable and comprises about 51 weight percent to about 100 weight percent of a polyhydroxyalkanoate; wherein the compostable fabric is biodegradable and demonstrates about 90% to about 100% conversion of organic carbon to carbon dioxide (CO₂) after 180 days as measured by ASTM D 5338 test method.

[0106] In other embodiments, the compostable fabric demonstrates about 90% to about 100% conversion of organic carbon to carbon dioxide (CO₂) after 162 days in the absolute as measured by ASTM D 5338 test method; or demonstrates about 90% to about 100% conversion of organic carbon to carbon dioxide (CO₂) after 143 days compared to a cellulosic control as measured by ASTM D 5338 test method.

[0107] In some embodiments, the compostable fabric is compostable in industrial aerobic facilities by demonstrating disintegration, wherein about 0% to about 10% of the compostable fabric's original dry weight remains after sieving on a 2.0 millimeter sieve after 84 days in a controlled composting test as measured in accordance with ISO 16929 with a minimum vessel volume of 35 Liters, or ISO 20200 under thermophilic aerobic composting conditions.

[0108] In some embodiments, the compostable fabric is compostable in industrial aerobic facilities by demonstrating a concentrations of regulated metals less than 50% of those prescribed for sludges or composts in a country where the compostable fabric is sold; or is compostable in industrial aerobic facilities by demonstrating a germination rate and a plant biomass of the compostable fabric composts shall be at least 90% that of corresponding blank composts for two different plant species following OECD Guideline 208 with the modifications found in Annex E of EN 13432.

[0109] In other embodiments, the polymeric composition further comprises a polylactic acid, a polycaprolactone, a polybutylene succinate, a polybutylene succinate adipate, a polybutylene adipate terephthalate, a starch, or any combination thereof; or an antioxidant, an ultraviolet (UV) stabilizer, or a combination thereof.

[0110] In some embodiments, the polymeric composition comprises 100% polyhydroxyalkanoate.

[0111] In other embodiments, the polyhydroxyalkanoate has a molecular weight of about 50,000 Daltons to about 2.5 million Daltons.

[0112] In one or more embodiments, the nonwoven fabric is formed by spunbonding, hydroentangling, needlepunching, thermal bonding, point bonding, or a combination thereof.

[0113] In other embodiments, the continuous filaments have an average diameter of about 10 to about 100 microns.

[0114] In some embodiments, the nonwoven fabric has a basis weight of about 20 to about 1,000 grams/square meter (gsm).

[0115] In other embodiments, the polymeric composition has a melt flow index (MFI) of about 1 to about 50 grams per 10 minutes as measured by ASTM D1238 test.

[0116] In some embodiments, the compostable fabric is an agricultural fabric.

[0117] In one or more embodiments, a method of making a compostable fabric includes extruding a polymeric composition to form continuous filaments, the polymeric composition being fully biodegradable and comprising about 51 weight percent to about 100 weight percent of a polyhydroxyalkanoate; and entangling the continuous filaments to form a nonwoven fabric.

[0118] In some embodiments, the extruding is by a melt spinning process at a temperature of about 120 to about 200 degrees Celsius.

[0119] In other embodiments, the entangling is hydroentangling and performed at a pressure of about 50 to about 300 Bars.

[0120] In embodiments, the polymeric composition comprises 100% polyhydroxyalkanoate; or the polyhydroxyalkanoate has a molecular weight of about 50,000 Daltons to about 2.5 million Daltons.

[0121] In other embodiments, the entangling is by spunbonding, hydroentangling, needlepunching, thermal bonding, point bonding, or a combination thereof.

[0122] In some embodiments, the continuous filaments have an average diameter of about 10 to about 100 microns; or the nonwoven fabric has a basis weight of about 20 to about 1,000 grams/square meter (gsm).

[0123] In other embodiments, the polymeric composition has a melt flow index (MFI) of about 3 to about 50 grams per 10 minutes as measured by ASTM D1238 test.

[0124] In some embodiments, the compostable fabric is an agricultural fabric.

[0125] Various embodiments of the present invention are described herein with reference to the related drawings. Alternative embodiments can be devised without departing from the scope of this invention. Although various connections and positional relationships (e.g., over, below, adjacent, etc.) are set forth between elements in the following description and in the drawings, persons skilled in the art will recognize that many of the positional relationships described herein are orientation-independent when the described functionality is maintained even though the orientation is changed. These connections and/or positional relationships, unless specified otherwise, can be direct or indirect, and the present invention is not intended to be limiting in this respect.

Accordingly, a coupling of entities can refer to either a direct or an indirect coupling, and a positional relationship between entities can be a direct or indirect positional relationship. As an example of an indirect positional relationship, references in the present description to forming layer "A" over layer "B" include situations in which one or more intermediate layers (e.g., layer "C") is between layer "A" and layer "B" as long as the relevant characteristics and functionalities of layer "A" and layer "B" are not substantially changed by the intermediate layer(s).

[0126] The following definitions and abbreviations are to be used for the interpretation of the

claims and the specification. As used herein, the terms “comprises,” “comprising,” “includes,” “including,” “has,” “having,” “contains” or “containing,” or any other variation thereof, are intended to cover a non-exclusive inclusion. For example, a composition, a mixture, process, method, article, or apparatus that comprises a list of elements is not necessarily limited to only those elements but can include other elements not expressly listed or inherent to such composition, mixture, process, method, article, or apparatus.

[0127] Additionally, the term “exemplary” is used herein to mean “serving as an example, instance or illustration.” Any embodiment or design described herein as “exemplary” is not necessarily to be construed as preferred or advantageous over other embodiments or designs. The terms “at least one” and “one or more” are understood to include any integer number greater than or equal to one, i.e. one, two, three, four, etc. The terms “a plurality” are understood to include any integer number greater than or equal to two, i.e. two, three, four, five, etc. The term “connection” can include an indirect “connection” and a direct “connection.”

[0128] References in the specification to “one embodiment,” “an embodiment,” “an example embodiment,” etc., indicate that the embodiment described can include a particular feature, structure, or characteristic, but every embodiment may or may not include the particular feature, structure, or characteristic. Moreover, such phrases are not necessarily referring to the same embodiment. Further, when a particular feature, structure, or characteristic is described in connection with an embodiment, it is submitted that it is within the knowledge of one skilled in the art to affect such feature, structure, or characteristic in connection with other embodiments whether or not explicitly described.

[0129] For purposes of the description hereinafter, the terms “upper,” “lower,” “right,” “left,” “vertical,” “horizontal,” “top,” “bottom,” and derivatives thereof shall relate to the described structures and methods, as oriented in the drawing figures. The terms “overlying,” “atop,” “on top,” “positioned on” or “positioned atop” mean that a first element, such as a first structure, is present on a second element, such as a second structure, wherein intervening elements such as an interface structure can be present between the first element and the second element. The term “direct contact” means that a first element, such as a first structure, and a second element, such as a second structure, are connected without any intermediary conducting, insulating or semiconductor layers at the interface of the two elements.

[0130] The terms “about,” “substantially,” “approximately,” and variations thereof, are intended to include the degree of error associated with measurement of the particular quantity based upon the equipment available at the time of filing the application. For example, “about” can include a range of $\pm 8\%$ or 5% , or 2% of a given value.

[0131] The flowchart and block diagrams in the Figures illustrate possible implementations of fabrication and/or operation methods according to various embodiments of the present invention. Various functions/operations of the method are represented in the flow diagram by blocks. In some alternative implementations, the functions noted in the blocks can occur out of the order noted in the Figures. For example, two blocks shown in succession can, in fact, be executed substantially concurrently, or the blocks can sometimes be executed in the reverse order, depending upon the functionality involved.

[0132] The corresponding structures, materials, acts, and equivalents of all means or step plus function elements in the claims below are intended to include any structure, material, or act for performing the function in combination with other claimed elements as specifically claimed. The description of the present invention has been presented for purposes of illustration and description, but is not intended to be exhaustive or limited to the invention in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art without departing from the scope and spirit of the invention. The embodiments were chosen and described in order to best explain the principles of the invention and the practical application, and to enable others of ordinary skill in the art to understand the invention for various embodiments with various

modifications as are suited to the particular use contemplated.

[0133] While the preferred embodiments to the invention have been described, it will be understood that those skilled in the art, both now and in the future, may make various improvements and enhancements which fall within the scope of the claims which follow. These claims should be construed to maintain the proper protection for the invention first described.

Claims

1. A compostable fabric comprising: a nonwoven fabric comprising continuous filaments comprising polymeric composition that is fully biodegradable and comprises about 51 weight percent to about 100 weight percent of a polyhydroxyalkanoate; wherein the compostable fabric is biodegradable and demonstrates about 90% to about 100% conversion of organic carbon to carbon dioxide (CO.sub.2) after 180 days as measured by ASTM D 5338 test method.
2. The compostable fabric of claim 1, wherein the compostable fabric: demonstrates about 90% to about 100% conversion of organic carbon to carbon dioxide (CO.sub.2) after 162 days in the absolute as measured by ASTM D 5338 test method; or demonstrates about 90% to about 100% conversion of organic carbon to carbon dioxide (CO.sub.2) after 143 days compared to a cellulosic control as measured by ASTM D 5338 test method.
3. The compostable fabric of claim 1, wherein the compostable fabric is compostable in industrial aerobic facilities by demonstrating disintegration, wherein about 0% to about 10% of the compostable fabric's original dry weight remains after sieving on a 2.0 millimeter sieve after 84 days in a controlled composting test as measured in accordance with ISO 16929 with a minimum vessel volume of 35 Liters, or ISO 20200 under thermophilic aerobic composting conditions.
4. The compostable fabric of claim 1, wherein the compostable fabric: is compostable in industrial aerobic facilities by demonstrating a concentrations of regulated metals less than 50% of those prescribed for sludges or composts in a country where the compostable fabric is sold; or is compostable in industrial aerobic facilities by demonstrating a germination rate and a plant biomass of the compostable fabric composts shall be at least 90% that of corresponding blank composts for two different plant species following OECD Guideline 208 with the modifications found in Annex E of EN 13432.
5. The compostable fabric of claim 1, wherein the polymeric composition further comprises: a polylactic acid, a polycaprolactone, a polybutylene succinate, a polybutylene succinate adipate, a polybutylene adipate terephthalate, a starch, or any combination thereof; or an antioxidant, an ultraviolet (UV) stabilizer, or a combination thereof.
6. The compostable fabric of claim 1, wherein the polymeric composition comprises 100% polyhydroxyalkanoate.
7. The compostable fabric of claim 1, wherein the polyhydroxyalkanoate has a molecular weight of about 50,000 Daltons to about 2.5 million Daltons.
8. The compostable fabric of claim 1, wherein the nonwoven fabric is formed by spunbonding, hydroentangling, needlepunching, thermal bonding, point bonding, or a combination thereof.
9. The compostable fabric of claim 1, wherein the continuous filaments have an average diameter of about 10 to about 100 microns.
10. The compostable fabric of claim 1, wherein the nonwoven fabric has a basis weight of about 20 to about 1,000 grams/square meter (gsm).
11. The compostable fabric of claim 1, wherein the polymeric composition has a melt flow index (MFI) of about 1 to about 50 grams per 10 minutes as measured by ASTM D1238 test.
12. The compostable fabric of claim 1, wherein the compostable fabric is an agricultural fabric.
13. A method of making a compostable fabric, the method comprising: extruding a polymeric composition to form continuous filaments, the polymeric composition being fully biodegradable and comprising about 51 weight percent to about 100 weight percent of a polyhydroxyalkanoate;

and entangling the continuous filaments to form a nonwoven fabric.

14. The method of claim 13, wherein extruding is by a melt spinning process at a temperature of about 120 to about 200 degrees Celsius.

15. The method of claim 13, wherein entangling is hydroentangling and performed at a pressure of about 50 to about 300 Bars.

16. The method of claim 13, wherein the polymeric composition comprises 100% polyhydroxyalkanoate; or the polyhydroxyalkanoate has a molecular weight of about 50,000 Daltons to about 2.5 million Daltons.

17. The method of claim 13, wherein the entangling is by spunbonding, hydroentangling, needlepunching, thermal bonding, point bonding, or a combination thereof.

18. The method of claim 13, wherein the continuous filaments have an average diameter of about 10 to about 100 microns; or the nonwoven fabric has a basis weight of about 20 to about 1,000 grams/square meter (gsm).

19. The method of claim 13, wherein the polymeric composition has a melt flow index (MFI) of about 3 to about 50 grams per 10 minutes as measured by ASTM D1238 test.

20. The method of claim 13, wherein the compostable fabric is an agricultural fabric.
