Use of bio-based polymers in agricultural exclusion nets: A perspective

Agneev Mukherjee [a,*], Simon Knoch [b], Gérald Chouinard [c], Jason R. Tavares [b] and Marie-Josée Dumont [a]

[a] Bioresource Engineering Department, McGill University, 21111 Lakeshore Rd., Ste-Anne-de-Bellevue, Québec H9X 3V9, Canada

[b] Department of Chemical Engineering, École Polytechnique de Montréal, Montreal, Quebec H3C 3A7, Canada

[c] Research and Development Institute for the Agri-Environment (IRDA), Saint-Bruno-de-Montarville, Québec J3V0G7, Canada

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[*] *Corresponding author and Page proof recipient:*

Agneev Mukherjee, PhD.
Department of Bioresource Engineering
McGill University,
21111 Lakeshore Rd.,
Ste-Anne de Bellevue,
Québec, Canada
H9X 3V9
1-514-398-7639
agneev.mukherjee@mail.mcgill.ca

Abstract

The use of exclusion netting as an Integrated Pest Management technique is likely to become increasingly important as a means to increasing crop yields whilst minimising pesticide use. However, the increasing use of these nets will also lead to a rise in greenhouse gas emissions in the agricultural sector and pose problems related to their end-of-life disposal. Employing biopolymers made from low-carbon and renewable biomass feedstock to fabricate exclusion nets can potentially resolve these issues by merging the benefits of the two emerging technologies. Despite this, there has only been limited work on the use of biopolymer netting in agriculture. By looking at the challenges needed to be overcome for biopolymers to be widely used as a netting material, this review aims to bridge the gaps between the two fields of research. To do so, the past work done on agricultural netting is discussed, with a focus on the implemented materials and their desired properties. After this, potential candidate biopolymers for manufacturing agricultural nets are pointed out, emphasizing their sustainability with respect to widely used Life Cycle Analysis (LCA) parameters, including the end-of-life treatment.

Keywords

Biopolymers, integrated pest management, agricultural nets, life cycle analysis, environmental impact

Nomenclature

ABS	Acrylonitrile butadiene styrene
DNDC	Denitrification-Decomposition
EPA	Environmental Protection Agency
EU	European Union
EVA	Ethylene vinyl acetate
GHG	Greenhouse gas
GWP	Global warming potential
HALS	Hindered amine light stabilisers
HDPE	High density polyethylene
HMF	5-hydroxymethylfurfural
i-PP	Isotactic polypropylene
IPM	Integrated pest management
LCA	Life cycle analysis
LDPE	Low density polyethylene
LLDPE	Linear low density polyethylene
LLITN	Long lasting insecticide treated nettings
LUC	Land use changes
MFI	Melt flow index
MMCF	Man-made cellulose fibres
PAR	Photosynthetically active radiation
PBS	Polybutylene succinate
PBT	Polybutyleneterephthalate
PCL	Polycaprolactone
PE	Polyethylene
PEF	Polyethylene-2,5-furandicarboxylate
PES	Polyethylene succinate
PET	Polyethylene terephtalate
PHA	Polyhydroxyalkanoates
PHB	Poly(3-hydroxybutyrate)

PICVD	Photoinitiated chemical vapor deposition
PLA	Polylactic acid
PP	Polypropylene
PPL	Polypropiolactone
PS	Polystyrene
PTT	Polytrimethylene terephthalate
PUR	Polyurethane
PVC	Polyvinyl chloride
TPS	Thermoplastic starch
TRACI	Tool for the reduction and assessment of chemical and other environmental impacts
UV	Ultraviolet
VLDPE	Very low density polyethylene

1. Introduction

Over the past century, the world population has grown at an exponential rate, from around 1.6 billion in 1900 to over 7.5 billion in 2017 (Biraben, 1979; Tanton, 1994; United Nations, 2017). This rapid growth has put an increasing strain on the finite planetary resources in recent decades. The agriculture sector has been particularly hard-hit, since its output has had to increase tremendously in order to feed the growing population. Thus far, this has been successfully accomplished via three means: expanding cropped area, increasing the cropping intensity, and raising yields (Food and Agriculture Organization, 2002). Of these, the third has been the most important, accounting for 77% of the growth in crop production between 1961 and 2007 (Food and Agriculture Organization, 2012). Expanding cropped area is likely to become increasingly problematic in the future given that more land will be dedicated to urbanisation or industrial use. Additionally, there are environmental concerns surrounding reclamation of land that is presently under forest cover or in wetlands for future agricultural use (Food and Agriculture Organization, 2012; Young, 1999). Furthermore, most of the prime agricultural land has already been used for cultivation, meaning that further expansion is likely to be on marginal lands with lower soil quality (Cassman, 1999; Young, 1999), which will further intensify the need to increase crop yields.

The dramatic increase in crop yield has largely been possible due to an accompanying increase in pesticide application worldwide, with pesticide sales rising 15-20 times between 1960 and 2004 (Oerke, 2005). An ideal pesticide would only affect the target species and be harmless to all other species, but this is almost never the case. In reality, conventional pesticides often harm the natural predators of the pests as well as humans, generate resistance in both target and non-target species over a period of time, and cause soil and water pollution (Aktar, Sengupta, & Chowdhury, 2009; Food and Agriculture Organization, 2002). To address this, Integrated Pest Management (IPM) techniques have been developed, wherein pesticide application is minimised by using pest-resistant crop varieties, crop rotation, bio-insecticides and traps, sterile insect release, and other methods (Food and Agriculture Organization, 2002; Prokopy & Kogan, 2009). Recognized by the European Union (EU) Commission as a key point for a more sustainable agriculture, such non-chemical methods should be preferred to chemical strategies if they induce "satisfactory pest control" (European Union, 2009). This last condition being difficult to determine, a survey of the efficiency of the implemented strategies is another key principle of the EU Directive (Barzman et al., 2015). Hence, IPM methods can be seen as a promising set of tools if they demonstrate their ability to prevent crop damage. Physical barriers such as fences, trenches, nets, bags and films are a class of IPM methods (Vincent, Hallman, Panneton, & Fleurat-Lessard, 2003). The use of bags, for instance, can prevent infestation of pomegranates and mangoes by the pomegranate butterfly and the mango fruit fly, respectively (Karuppuchamy & Venugopal, 2016). Several success stories have been reported on the use of nets, such as a dramatic increase in cabbage yield on using low cost pest exclusion nets in Kenya (Kiptoo et al., 2015), a rise in the marketable yield of cucumbers through the use of fine mesh netting screenhouses in Hawaii, USA (Chong Ho, 2008), and a reduction in the infestation of tomato by the yellow leaf curl virus on using insect exclusion screens in Israel (Berlinger, Taylor, Lebiush-Mordechi, Shalhevet, & Spharim, 2002).

However, despite the success stories mentioned in the preceding paragraph, a persistent concern is that the nets in use are predominantly produced from fossil fuel feedstock. This means that their use, similarly to fertilisers and pesticides, is an indirect addition to the Greenhouse Gas (GHG) emissions in the agriculture sector. The use of biopolymers, derived from renewable biomass feedstock, is a potential alternative. This will allow a merger of the benefits of biopolymers and exclusion netting, both in themselves eco-friendly technologies, to create a more sustainable alternative to pesticides. This review focuses on the use of bio-sourced polymers for fabricating exclusion netting in agricultural applications, shining a spotlight on their credentials as environmentally friendly alternatives to existing fossil-based polymers.

2. Exclusion systems in agriculture: Description and effectiveness

Although nets have been used in agriculture for decades, their use has increased in recent years as a means of protecting plants from pests, climatic conditions such as hail, wind and frost, and from excessive sunlight (Castellano, Mugnozza, et al., 2008; Chouinard, Firlej, & Cormier, 2016). The most widely used agricultural nets are made from clear high-density polyethylene (HDPE), as this material is non-toxic, recyclable, waterproof, and has good mechanical characteristics in terms of tensile strength (13-51 MPa), Young's modulus (800-1005 MPa), strength at break (35 MPa) and elongation at break (250-1200%) (Castellano, Mugnozza, et al., 2008; Ramsay, Langlade, Carreau, & Ramsay, 1993; Wypych, 2016). Polypropylene (PP) is the second-most commonly used plastic for making nets, being used especially for non-woven nets (Castellano, Mugnozza, et al., 2008; Scarascia-Mugnozza, Sica, & Russo, 2012).

2.1. Characteristics of agricultural nets

The desired properties of the materials used for making agricultural nets depend to an extent on the specific application in question. Nevertheless, there are a few important characteristics that these nets, and specifically those used for exclusion purposes, should have. These include:

a) Durability: Any net used for agricultural purposes will be subjected to numerous factors that affect its durability and lifetime. Generally, the useful life of a material can be considered to be finished once its mechanical strength drops below 50% of the original value (Dilara & Briassoulis, 2000). A major factor affecting the mechanical properties of the nets is ultraviolet (UV) radiation. Most commercial nets have a solar radiation resistance equivalent to around 17-33 GJ m^{-2} corresponding to about 5-6 years of solar irradiance in mild climates such as Mediterranean areas, or 3-4 years in tropical regions (Castellano, Mugnozza, et al., 2008). Since the amount of UV radiation received annually varies from around 3 GJ m^{-2} in northern countries to over 8 GJ m^{-2} in tropical equatorial climates (World Energy Council, 2016), the lifetime of the nets also varies according to the location. UV stabilisers such as hindered amine light stabilisers (HALS) and nickel quenchers are sometimes added to the plastic to absorb and dissipate the UV radiation, thereby delaying the degradation process (M Guo & Horsey, 1998; Kaci, Sadoun, & Cimmino, 2000). Other factors, such as the polymer chain length, sheet thickness, additives used, environmental conditions (such as wind and hail storms), exposure to agrochemicals, contact with corrosive materials, etc., also affect the net lifetime (Castellano, Mugnozza, et al., 2008; Scarascia-Mugnozza et al., 2012). Agricultural nets are subject to a range of American and European standards regarding their durability, mechanical, physical and radiometric requirements (Scarascia-Mugnozza et al., 2012). For example, as per ASTM 2002 and ISO 527-3, the minimum tensile strength at break is 20 MPa for films with a thickness below 50 µm, and 16 MPa for films thicker than 50 µm (Scarascia-Mugnozza et al., 2012).

b) Shading factor: The shading factor refers to the ability of a net to absorb and reflect in the visible spectrum of solar radiation (Castellano, Candura, & Scarascia Mugnozza, 2008). A high shading factor can be considered to be a positive feature when one desired result of applying the net is reducing the incoming solar irradiation that can cause plant surface temperature to rise above damaging levels. For exclusion nets, however, a high shading factor may be detrimental, especially under temperate climates, since shading can profoundly affect photosynthesis rates, crop yields and fruit ripening (Dussi et al., 2005; Ilić, Milenković, Đurovka, & Kapoulas, 2011; S. J. Kim, Yu, Kim, & Lee, 2011; Lin, McGraw, George, & Garrett, 1998;

McDermott & Nickerson, 2014; Mupambi et al., 2018). The shading factor can be controlled by changing the net colour, with black, green, red, yellow, blue, white and grey nets, in addition to clear ones, being used for different applications (Castellano, Candura, et al., 2008). Alongside modifying the shading factor, net colouring can also be used to control sunburn in fruits such as apples (Racsko & Schrader, 2012), influence plant physiology (Mupambi et al., 2018), decrease insect penetration based on their colour preferences (Ben-Yakir, Hadar, Offir, Chen, & Tregerman, 2008), increase fruit size and quality (Basile et al., 2012), and even improve the ability of workers to judge ripeness while harvesting a crop (Stamps, 2009).

c) Mesh size: The two major dimensions of a net are the thickness and the mesh size. Generally, the net thickness varies from 0.25 to 0.32 mm. The mesh size, on the other hand, is generally between 0.2 and 3.1 mm for insect nets (Castellano, Mugnozza, et al., 2008). Mesh size is directly related to net porosity (Π), which is defined as the ratio between the open and the total area of the net surface (Abdel-Ghany & Al-Helal, 2011). Occasionally, this parameter can instead be expressed in terms of net solidity (Φ), which is the complementary value of porosity ($\Phi = 1 - \Pi$) (Castellano, Mugnozza, et al., 2008).

Net porosity is important, as it affects other properties such as the weight, the shading factor and the ventilation rate of the net. A decrease in the screen porosity broadly results in a decrease in the relative ventilation rate of the enclosed area (Pérez Parra, Baeza, Montero, & Bailey, 2004). For instance, it has been estimated that anti-thrips and anti-aphid nets can reduce ventilation by 40 to 50% (Fatnassi, Boulard, Demrati, Bouirden, & Sappe, 2002). Additionally, reduced porosity can also increase temperature and humidity, and reduce sunlight entering the net (Abdel-Ghany & Al-Helal, 2011; Pérez Parra et al., 2004). Correlations for calculating the discharge coefficients for greenhouses having exclusion netting exist, and should be used when deciding on the suitability of a particular net (Montero, Muñoz, & Antón, 1997). Another parameter quantifying the effect of the net itself on the air stream is the loss coefficient, expressing the pressure drop through the net. It has been found that this parameter is a function of net porosity, hole size and Reynolds number of the fluid. An elongated shape of the mesh induces a change in the air flow experiments similar to a net porosity increase, suggesting the use of equivalent net porosity for ventilation studies (Castellano, Mugnozza, et al., 2008).

On the other hand, reduced mesh size may be necessary to keep out very small insects. While the spotted wing drosophila (*Drosophila suzukii*), which has a thoracic width of 700-1240 µm, can be kept out using nets with a mesh size of 980 µm, excluding the silverleaf whitefly (*Bemisia argentifolii*), which has a thoracic width of 239 µm, would require a mesh size of 240 µm (Kawase & Uchino, 2005; Teitel, 2007). This difference might arise from the different morphologies of the targeted insects. However, mesh size and airflow resistance do not always correspond to the achieved degree of exclusion. It has been shown that many commercial nets with high resistance to air flow do not exclude whiteflies and thrips more efficiently than other screens with less airflow resistance, as insects are often able to squeeze through holes narrower than themselves (Bell & Baker, 2000). This shows that the degree of exclusion cannot be predicted solely from the thoracic width and hole size, but other factors such as the hole geometry and behaviour also play a part (Bethke, 1991).

At the same time, a screen that excludes the natural enemies of the pests but is unable to prevent small pests from entering may actually lead to lower crop yields (Dobson, 2015). As an example, exclusion nets have been seen to cause an increase in aphid populations in apple orchards, which has been hypothesised to be caused by the exclusion of predatory species (Chouinard et al., 2017). Also, it has been postulated that moths escaping after laying eggs within the nets may lead to the moths evolving to reproduce under the nets, which may be deemed to be a form of 'resistance' to exclusion netting (Siegwart, Pierrot, Toubon, Maugin, & Lavigne, 2012). The impact of netting on pollinators also needs to be considered. A study on coffee plantations, for instance, found a 14.6% increase in production when pollinators could visit coffee plantations without exclusion netting (De Marco & Coelho, 2004). In another study on apples, row-by-row exclusion systems were used to exclude pests but required the nets to be opened during bloom for pollination (Chouinard et al., 2016).

A balance, therefore, needs to be found for the pore size so as to maximise the exclusion of the target species while minimising the effect on the biotic and abiotic conditions. This may be done, for instance, by comparing the screens based on a combination of their geometric parameters and insect exclusion effectiveness (Cabrera, Lopez, Baeza, & Pérez-Parra, 2006). In the market, manufacturers commonly make available nets tailored to specifically meet one or more of the above criteria, for instance nets for 'optimal airflow', 'best light transmission', 'cost effectiveness', etc. (Dubois Agrinovation, 2018).

To meet the requirements, three types of weaves are commonly used in agricultural nets, namely flat, English and knitted or Raschel (Briassoulis, Mistriotis, & Eleftherakis, 2007; Castellano, Candura, et al., 2008). Those different types will produce nets of tuneable mechanical properties, which importance is related to the use of the product, as mentioned later in the paragraph. The flat weave gives a light and stable structure but induces a relatively high stiffness and low available deformation. The produced mesh is most often orthogonal, with weft perpendicular to warp, requiring low technological investment. This weave is mostly chosen for anti-hail or shading nets, but can also be implemented for relatively large mesh exclusion nets. A modification of this type is the English weave, where two weft fibres will hold the warp yarn, providing a more rigid structure, mostly used for protection against strong meteorological events such as hail. The last type is the knitted net, where all yarns are linked with each other through nodes, creating an unravelling-resistant structure prone to relatively high deformation. The commercially available nets indicate a prevalence of the knitted type. Some non-woven varieties are also sold, such as Agryl fleeces (PP) (Avintiv, 2018) or Yaolong non-woven (PLA) (Yaolong Spunbonded Nonwoven Technology Co., 2018). No study has been conducted on their life time or viability in field conditions, to the authors' knowledge.

The above provides a brief overview of the characteristics generally required for agricultural netting. Specific circumstances may require additional requirements to be fulfilled. For instance, although past studies have found that netting can reduce mechanical bruising in fruit trees (Chouinard et al., 2016), excessively stiff netting may lead to crop abrasion if the crops are planted too closely to the netting in windy regions. It is therefore necessary for growers to consider both past experiences and their individual circumstances while deciding on the netting characteristics.

2.2. Examples of deployment of agricultural exclusion nets

The reason that exclusion nets are being used to an increasing extent in agriculture arises from their past success in protecting a variety of crops in fields and greenhouses around the world. Table 1 shows the work that has been carried out worldwide in this area over the past two decades. Netting has been used to protect both horticultural crops like cabbage and tomato, and tree fruit crops like apple and papaya. On the other hand, there is a conspicuous lack of trials on field crops such as rice and wheat, suggesting that it may be impractical to apply netting to protect hundreds or thousands of hectares of crop land.

Table 1: Overview of exclusion netting deployment for various crops

Protected crop	Target pest(s)	Location	Reference
Cabbage (*Brassica oleracea* var *capitata*)	*Plutella xylostella* L.; *Myzus persicae; Lypaphis erysimi; Brevicoryne brassicae*	Kabete and Thika, Kenya	(Kiptoo et al., 2015)
Japanese cucumber	*Bactrocera cucurbitae; Bemisia tabaci; Thrips palmi; Diaphania nitidales*	Hawaii, USA	(Chong Ho, 2008)
Tomato and bell pepper	*Spodoptera exigua; S. eridania, S. frugiperda; Manduca quinquemaculata*	Alabama, USA	(Majumdar & Powell, 2010)
Tomato	*Bemisia tabaci* (Gennadius)	Israel	(Berlinger et al., 2002)
Blueberry	*Drosophila suzukii*	Québec, Canada	(Cormier, Veilleux, & Firlej, 2015)
Cabbage (*Brassica oleracea* var *capitata*)	*Plutella xylostella; Crocidolomia pavonana;* *Spodoptera litura*	Solomon Islands	(Neave, Kelly, & Furlong, 2011)
Bell pepper (*Capsicum annuum*)	*Halyomorpha halys*	Kentucky, USA	(Dobson, 2015)
Raspberry	*Drosophila suzukii*	Michigan, USA	(Leach, Van Timmeren, & Isaacs, 2016)

French bean (*Phaseolus vulgaris*)	*Bemisia tabaci* (Gennadius); *Aphis fabae* (Scopoli)	Njoro, Kenya	(Gogo et al., 2014)
Tomato (*Solanum lycopersicum*)	*Lyriomyza sp.; Helicoverpa armigera; Thrips tabaci; Tetranychus sp.; Bemisia tabaci; Aphis sp.*	Njoro, Kenya	(Gogo, Saidi, Itulya, Martin, & Ngouajio, 2012)
Tomato	*Tuta absoluta (Meyrick)*	Bekalta, Tunisia	(Harbi, Abbes, Dridi-Almohandes, & Chermiti, 2015)
Apple	*Cydia pomonella*	Avignon, France	(Sauphanor, Severac, Maugin, Toubon, & Capowiez, 2012)
Peach and nectarine	*Bactrocera tryoni*	Queensland, Australia	(Lloyd, Hamacek, George, Nissen, & Waite, 2005)
Maine wild blueberry (*Vaccinium angustifolium* Aiton)	*Drosophila suzukii*	Maine, USA	(Alnajjar, Collins, & Drummond, 2017)
Papaya	Different planthoppers and leafhoppers; *Amblypelta* sp.	Queensland, Australia	(Walsh, Guthrie, & White, 2006)
Swede	*Delia radicum; D. floralis*	Smøla, Norway	(Meadow & Johansen, 2005)
Apple and pear	*Cydia pomonella*	Rhone, France; Emilia-Romagna, Italy	(Alaphilippe et al., 2016)
Apple	*Aphis pomi; Rhagoletis pomonella; Typhlocyba pomaria; Cydia pomonella; Conotrachelus nenuphar; Lygus lineolaris*	Québec, Canada	(Chouinard et al., 2017)
Apple	*Dysaphis plantaginea*	Avignon, France	(Dib, Sauphanor, & Capowiez, 2010)

Tomato	Aphids and thrips	Italy	(Giordano, Pentangelo, Graziani, & Fogliano, 2003)
Cabbage	*Plutella xylostella*; *Brevicoryne brassicae*; *Myzus persicae*; *Lipaphis erysimi*	Montpellier, France; Cotonou, Benin	(S. Simon et al., 2014)
Olive	*Philaenus spumarius*	Valenzano, Italy	(Di Palma et al., 2017)

Multiple choices are available in terms of crop protection systems, as illustrated in Figure 1 for pome and stone fruit crops, which includes prototypes for complete exclusion systems (Figs. 1A and 1B). Some crops might use other types of netting exclusion system, such as tunnels for tomato culture (Giordano et al., 2003). The adopted choice will therefore depend on the availability of the different systems, their cost effectiveness, the capital expenditure required, the knowledge and experiences of the operators, etc.

Fig. 1 (A) and (B): Complete exclusion prototypes for apple trees (Chouinard et al., 2016)

2.3. Economics of agricultural exclusion netting

A major factor that cultivators need to consider when deciding whether to implement netting is the required investment. For instance, the per hectare cost of netting fruit orchards in Australia in 2008 was estimated to range from A$ 17,000-72,000 (US$ 14,000-61000 in 2008), with even higher costs possible in case of difficulties associated with topography, orchard layout and tree size (Rigden, 2008). Another study in France found that the use of netting for protecting apples represented 25% of the planting costs for the first three years and 7% of annual production costs afterwards (Stévenin, 2011). Therefore, the use of nets may not be economically feasible in all cases.

As an example, a study on soft fruits in Italy found that the use of exclusion nets as an addition to conventional IPM is only economically profitable in case of high pest pressure levels (Del Fava, Ioriatti, & Melegaro, 2017). Likewise, a 2014 study on protecting blueberry fields from Spotted Wing Drosophila in New York, USA, estimated that the annual cost of covering of blueberry crops with netting would be around US$ 1,143/acre, excluding labour (McDermott & Nickerson, 2014). This is much higher than the estimated costs for controlling drosophila by other means, and hence the authors postulated that netting may be a more economically feasible option for organic or small acreage plantations, or in plantations where an additional benefit (e.g. a reduction in bird damage) can be obtained. For fruit trees, the age of the orchard is another consideration, with the limited returns from low-yielding young trees meaning that the deferment of netting until the orchard is more mature may be more financially sensible (Rigden, 2008).

An early example of economically sustainable adoption of insect exclusion nettings was in tomato production in Israel. Taylor, et al. estimated that the adoption of insect exclusion netting in tomato-producing greenhouses in the period between 1984-89 led to a benefit of US$ 112.9 million to the Israeli economy, a success story which meant that by the late 1990's, insect screening had become a standard pest management technique for both greenhouse- and field-grown tomatoes in Israel (Taylor, Shalhevet, Spharim, Berlinger, & Lebiush-Mordechi, 2001).

Depending on the type of crop and the size and type of the enclosure, the cost incurred in erecting enclosure netting can be offset to a large extent by the accompanying reduction in the cost of insecticide application. For instance, a study on cabbage production in Benin found that insecticide costs were reduced by 68-95% when shifting from unnetted protection to netted protection, and the higher margins meant that the cost benefit ratio improved from 1:1.58 to 1:2.66 when netting was applied (Vidogbéna et al., 2015). Mazzi et al., on the other hand, compared the cost of using enclosure netting as a component of IPM measures with the additional harvest and disposal costs that would be incurred due to infestation of sweet cherry by *Drosophila suzukii* in Switzerland. They found that an investment of CHF 1857 (US $ 1900 in 2017) per hectare on IPM, of which CHF 410/ha (US $ 420/ha) was directed towards enclosure nets, could avoid harvest and disposal costs ranging from CHF 22,000 to 69,000/ha (US $ 22,500-70,500/ha) depending on the degree of fruit infestation (Mazzi, Bravin, Meraner, Finger, & Kuske, 2017). A 2010 study on protecting cabbages in the Solomon Islands also found a positive net present value for netting for two out of the three sites tested (Neave et al., 2011).

The cost of exclusion netting is evidently an important subject on which limited information is presently available. As its use becomes more widespread, it can be expected that more studies will be conducted to provide a better understanding of the conditions under which the use of exclusion netting is economically viable.

2.4. Modified agricultural exclusion nets

Most of the nets that have been used worldwide for insect exclusion have relied on forming a physical barrier between the protected area and the surroundings. However, there have been attempts to increase the efficacy of the nets by adding other protection mechanisms. One example of this is the development of long-lasting insecticide treated nets (LLITNs), which combine physical and chemical tactics for insect exclusion. While an insecticide may be sprayed onto the surface of a net, LLITNs are generally made by incorporating the insecticide during yarn fabrication in the factory. The advantage of LLITNs with incorporated insecticides over their coated counterparts is that the insecticide present within the fibres diffuses over time to the surface of the yarn, replacing the insecticide on the surface that has been washed off or otherwise lost (Ouattara, Louwagie, Pigeon, & Spanoghe, 2013). This means that incorporated LLITNs can last over three years under field conditions (Dáder et al., 2015). An alternative method under development is the deposition of silver nanoparticles on HDPE nets to induce antimicrobial properties to lower the spread of bacterial contamination (De Simone et al., 2014).

Numerous field tests have been conducted on LLITNs, with limited success. Tunnel screens impregnated with deltamethrin were shown to be effective in protecting cabbage from *Lipaphis erysimi* (turnip aphid), *Plutella xylostella* (diamondback moth) and *Hellula undalis* (cabbage webworm) to a greater extent than conventional insecticide treatment; however, they were ineffective against *Spodoptera littoralis* (cotton leafworm) (Licciardi et al., 2008). Similarly, bifenthrin-treated nets were effective in curtailing *Aphis gossypii* (cotton aphid) infestation of cucumber plants, but were ineffective against *Bemisia tabaci* (sweet potato whitefly) (Dáder et al., 2014). Bifenthrin LLITNs may have an additional benefit of being compatible with *Amblyseius swirskii*, a predatory mite which is an important natural enemy of whiteflies and thrips (Fernandez et al., 2017). LLITNs treated with α-cypermethrin and deltamethrin have been shown to inflict up to 100% mortality on the *Popillia japonica* (Japanese beetle) after as little as 5 s of exposure, meaning that these nets can potentially help curtail the rapid spread of this invasive species (Marianelli et al., 2018). Deltamethrin-treated nets have also been found to be effective in protecting citrus trees from *Diaphorina citri* (Asian citrus psyllid) infestation (Trujillo, 2014), and in controlling populations of *Halyomorpha halys* (brown marmorated stinkbug) (Kuhar, Short, Krawczyk, & Leskey, 2017), *Leptinotarsa decemlineata* (Colorado potato beetle) and *Conotrachelus nenuphar* (plum curculio) (Gökçe, Bingham, & Whalon, 2018).

Against the above success stories, certain interventions with LLITNs have shown less promising results. A study on cabbage protection in Kenya found that nets impregnated with α-cypermethrin only had an additional pest control benefit as compared to ordinary nets at the nursery level, not in the field (Kiptoo et al., 2015). Similar nets, when used for protecting French beans, reduced infestation as compared to untreated nets, but did not ultimately increase pod yield or quality (Gogo et al., 2014).

By providing a dual barrier for pests to overcome, LLITNs can be used to replace untreated nets having smaller hole sizes (Dáder et al., 2014). This leads to improved ventilation in the enclosed area, alleviating some of the problems mentioned in Section 2.1.c. Their use also reduces the need for pesticide application in the fields (Dáder et al., 2014; Licciardi et al., 2008). Nevertheless, the use of LLITNs also has certain drawbacks. Firstly, as noted above, they can be ineffective against certain pests. Another is the fact that their effectiveness deteriorates over a period of time when deployed in fields, primarily due to sun exposure (Dáder et al., 2014). The compatibility of these nets with the pests' natural enemies that are used in biocontrol also needs to be evaluated (Dáder et al., 2015). Finally, the long-term toxicological impacts of these nets need evaluation.

Another method of increasing screen effectiveness is electrification, as used in warehouse or greenhouse windows. Matsuda, et al. found that these screens can be used to repel insects and spiders belonging to a range of different taxonomic ranks (Matsuda et al., 2015). The nets in question are made of stainless steel, with insulated iron conductor wires placed between two grounded stainless steel meshes. While insects that manage to enter the enclosure from the entrance or via other means are captured due to the electrostatic attraction between the negatively charged screen and the positively charged insects, insects contacting the exterior of the screen detect the field using their antennae and avoid entry (Matsuda et al., 2011). Thus, insect vectors such as whiteflies, green peach aphids, western flower thrips and shore flies can be excluded, while allowing much higher air penetration than would have been possible using unelectrified screens (Kakutani et al., 2012). Similar to the other innovations mentioned in this section, this technology also requires larger-scale and longer-period validation in terms of effectiveness, safety, cost, and other parameters. In recent years, research has been conducted on electrically conductive polymers, including polypropylene and polyethylene composites (Das & Prusty, 2012; Gulrez et al., 2014), and recently self-healing variants have appeared (Zhang & Cicoira, 2017). Therefore, the possible use of conductive polymers to fabricate these nets also needs to be considered.

A recent addition to the list of modifications researched is an increase in the hydrophobicity of the polymers used for net manufacture. Current exclusion nets allow rainwater to pass through the mesh, which adds to the problem of increased humidity alluded to in Section 2.1.c. This can, for instance, lead to infestation from apple scab, *Venturia inaequalis*, in apple orchards. Treating the net material with a superhydrophobic coating can lead to rainwater droplets trickling along the surface of the exclusion net, thereby minimising water ingress into the protected area. Bérard, et al. trialled the use of photo-initiated chemical vapour deposition (PICVD) for treating HDPE and polyethylene terephthalate (PET) with a commercial superhydrophobic material, and found that the modified nets successfully reduced water entry inside the net (Berard, Patience, Chouinard, & Tavares, 2016). The deployment of such netting can be done with row-by row systems, or full-block systems with water discharge lines. These nets do not generally prevent water from reaching the ground and the roots, but only protect the foliage from getting wet. Long duration field trials will allow an evaluation of the suitability of this technology for commercialisation, and determine in which kind of application this property would lead to a better harvest quality.

The use of UV-absorbing materials in agricultural applications has been researched extensively due to their effects on insect behaviour, and this might be relevant for future combination with exclusion netting strategies. Vision and olfaction are the two primary cues used by insects to orient themselves towards their host plants (Antignus, 2000). Their ocular photoreceptors capture information over a large bandwidth of electromagnetic radiation- UV (100-400 nm), visible or photosynthetically active radiation (PAR, 400-700 nm), and far red (700-800 nm) (Díaz & Fereres, 2007). However, the UV component is especially important for their orientation, navigation, feeding and sexual interaction (Antignus & Ben-Yakir, 2004). A net made of UV-absorbing material can therefore reduce the population of harmful arthropods both by repelling the insects via radiation reflection and by affecting their population growth (Legarrea, Karnieli, Fereres, & Weintraub, 2010). Studies have shown that when given a choice between a space with UV radiation and one from which it is absent, many insect species avoid the latter. This, however, is also true for pollinating insects, and hence needs to be applied with caution (Shimoda & Honda, 2013). The compatibility of UV-absorbing nets with natural predators also needs to be considered (Díaz & Fereres, 2007; Legarrea, Fereres, & Weintraub, 2009).

While polyvinyl chloride (PVC) and polycarbonate have intrinsic UV-absorbing properties, polyethylene can also be modified by adding UV-absorbing compounds to the raw material during manufacture. This can allow the development of films that block over 95% of UV radiation while simultaneously transmitting 80% of PAR (Antignus & Ben-Yakir, 2004). The materials in question may be finetuned to filter out a certain spectrum of UV radiation while allowing UV light of a different wavelength to pass through. For example, cellulose diacetate absorbs UV-C (100-280 nm) radiation but transmits UV-B (280-315 nm) and UV-A (315-400 nm) wavelengths (Díaz & Fereres, 2007). On the other hand, polyethylene terephthalate (PET) can be modified to exclude wavelengths between 250 and 370 nm while allowing radiation of shorter and longer wavelengths to pass (Teng & Yu, 2003). Likewise, the absorbance of polystyrene is very high for UV-B and the upper range of UV-C, but drops sharply on both sides of the spectrum (Li, Zhou, & Jiang, 1991). Blends of different polymers, therefore, can be used to selectively eliminate a portion of the UV spectrum.

The possible negative effects of the UV-absorbing compounds need to be considered before their application. For example, cellulose diacetate, mentioned in the preceding paragraph, may have a cytotoxic effect on cucumber plants due to the release (via outgassing) of phthalates or breakdown products (Krizek & Mirecki, 2004). Additionally, the stability of the UV-absorbing additives needs to be considered. Often, commonly used agrochemicals severely impair their performance, with their UV-screening effect also diminishing as a function of time, especially if they are too volatile (Simpson, 2003). The additives therefore need to be selected so as to remain relatively stable under ambient solar UV radiation for up to four years (Krizek, Clark, & Mirecki, 2005). Overall, though, it can be stated that the positive results of the use of UV-absorbing nets that have been reported for lettuce (Díaz, Biurrún, Moreno, Nebreda, & Fereres, 2006; Sal et al., 2009), sweet pepper (Ben-Yakir, Antignus, Offir, & Shahak, 2012; Legarrea et al., 2009), tomatoes (Antignus, Lapidot, Hadar, Messika, & Cohen, 1998; Ben-Yakir et al., 2012), and cucumbers (Antignus et al., 1998; Ben-Yakir et al., 2008), among others, mean that their use is likely to become increasingly prevalent in the future.

3. Rationale for use of bio-based materials for exclusion netting

Tools for theoretically computing the sustainability of crop protection methods are available, namely DEXiPM®, a multi-criteria decision software derived from DEXi for Pest Management (Pelzer et al., 2012) which shows that exclusion nets reduce the environmental impact of the culture due to the reduction of pesticide use (Alaphilippe et al., 2013). It can be noted that this software uses mostly qualitative data and does not take into account the end-of-life of the material, so that its response to input might not be of high scientific interest. Indeed, some issues related to polymeric nets arise when the whole process is taken into account.

One major concern surrounding the plastic netting being used at present is regarding their end-of-life disposal. If abandoned following use, they lead to soil and water pollution. If combusted, they can lead to emissions of large quantities of CO_2 and air pollutants (Briassoulis, 2004; Scarascia-Mugnozza et al., 2012). Plastic wastes also account for a large proportion of landfill waste, as well as being a leading contributor to marine pollution. Efforts, therefore, have been made to find bio-, thermo- or photo-degradable plastics, which degrade automatically in the presence of microorganisms, heat or solar radiation (Ammala et al., 2011; Benítez et al., 2013; Scarascia-Mugnozza et al., 2012).

The other major issue is the emission of GHGs caused by the manufacture of the netting material using fossil fuel resources. Life Cycle Analysis (LCA) of HDPE commercial nets has shown that the use of this polymer accounts for 52% of the Global Warming Potential (GWP) of the whole net manufacturing process (Dassisti, Intini, Chimienti, & Starace, 2016). The GWP expresses the impact of a process in terms of mass-equivalent CO_2 release and its greenhouse effect on the climate in a specific time frame. The most pertinent method to decrease the GWP of the agricultural net production is therefore to reduce the impact of the raw material, which could be done by replacing HDPE by a bio-based polymer. Biopolymers, that is, polymer made from biomass feedstocks, are often considered to be carbon-neutral (see Section 6.2 for a detailed discussion). They are also usually biodegradable (elaborated upon in Section 6.4), and hence the problem of disposal associated with fossil fuel-based plastics may also be eliminated by their replacement with biopolymers. The following sections show how the use of biopolymer exclusion nettings in agriculture is worthy of further investigation.

4. Biopolymers- an overview

Before dealing with the subject of using biopolymers for fabricating exclusion nets, it is pertinent to have a brief overview of the field of biopolymers. Biopolymers have long been a niche product, to the extent that they accounted for only 1% of the 300 million tonnes of plastic produced worldwide in 2013. From this small base, however, their production is poised to expand rapidly, with 4.2 million tonnes being produced in 2016, and 6.1 million tonnes being the projected production in 2021 (Lewandowski, 2018). The present focus in this sector is on improving the intrinsic properties of the material, reducing costs, increasing yields and developing better feedstock supplies, although it has been argued that the sustainability of biopolymers must also be communicated more effectively to consumers to encourage wider adoption (Iles & Martin, 2013; Sudesh & Iwata, 2008).

A large number of bio-based polymers have been evaluated, and some of the most prominent ones are profiled below.

4.1 Starch-based polymers

Starch is a polysaccharide used by many photosynthetic plants as a storage reserve. It is produced commercially from several sources, such as corn, wheat, potato and pea, and has found applications in several food and non-food industries. Starch plastics were among the earliest biodegradable biopolymers to be commercialised on a large-scale, as reflected by the fact that starch-based materials accounted for 85-90% of the total market for biodegradable materials in 2001 (Bastioli, 2001). Based on their preparation process, starch plastics can be broadly categorised into five non-mutually exclusive groups: partially fermented starch, thermoplastic starch (TPS) or destructurised starch, chemically modified starch, starch blends, and starch composites (Laycock & Halley, 2014; Shen, Haufe, & Patel, 2009). Of these, starch blends - produced by mixing native, chemically modified or destructurised starch with other petrochemical, bio-based or inorganic compounds – are the plastics that come the closest to replicating the mechanical properties of widespread petroleum-derived polyolefins such as low density polyethylene (LDPE), HDPE and polystyrene (PS), and it is in their replacement that starch plastics appear to have the greatest potential (Laycock & Halley, 2014; Shen et al., 2009).

Among the challenges to overcome is the fact that the composition of starch varies according to its source. Starch is fundamentally composed of two different polymers, amylose and amylopectin, and it has been shown that their ratio affects the physical and chemical properties of the starch, as well as of the products obtained from it (Morris, 1990; Rindlav-Westling, Stading, & Gatenholm, 2002; Zou et al., 2012). In case of starch-based polymers, the starch composition affects properties such as the stress-strain relaxation behaviour, the crystallinity and the morphology (Rindlav-Westling et al., 2002; van Soest & Essers, 1997). Moreover, the fact that most starch-based polymers are biodegradable can work against them in exclusion netting applications, where a long lifetime would be preferable from an economic standpoint.

As HDPE is the most widely used polymer for the manufacture of agricultural nets, a starch-based polymer that can replicate its properties would be a promising alternative material. For instance, a thermoplastic starch composite made of maize starch and reinforced with sugarcane bagasse has been found to have mechanical properties comparable to HDPE (Dogossy & Czigany, 2011). Since the mechanical properties of starch-based polymers tend to deteriorate seriously when the starch content exceeds 25 wt%, the addition of co-polymers or functional groups such as maleic anhydride or oxazoline may be necessary (Kalambur & Rizvi, 2006). This has led to extensive research on producing starch plastics with better thermal and mechanical properties, often using additives such as natural fibres (Nagy, Fodorean, Co˜a, Cioica, & Gyorgy, 2017), proteins (Gonzalez-Gutierrez, Partal, Garcia-Morales, & Gallegos, 2010) or nanocomposites (Mose & Maranga, 2011). The role of such additives needs to be synchronised with the requirements of agricultural netting, as they often exert contrasting influences on the material properties. As an example, the addition of vegetable oil to polyethylene-starch blends improves the film quality but also accelerates film degradation, with the oil acting as a prooxidant (Sastry, Satyanarayana, & Rao, 1998).

4.2 Cellulose polymers

Cellulose is a major component of the cell walls of most plant cells, and is consequently the most abundant organic polymer on earth (Klemm, Heublein, Fink, & Bohn, 2005). Although an isomer of starch, and likewise a polyglucan, it is much harder to depolymerise or modify, owing both to the β-linkages in its primary structure and the hydrogen bonds existing between neighbouring cellulose chains (Shen et al., 2009). Polymers made from cellulose can broadly be classified into cellulose esters (e.g. cellulose acetate, cellulose nitrate), cellulose ethers (e.g. carboxymethyl cellulose) and regenerated cellulose (e.g. cellophane) (Shen et al., 2009; J. Simon, Müller, Koch, & Müller, 1998). The regenerated cellulose polymers called man-made cellulose fibres (MMCF), such as viscose, have so far seen the largest application among cellulosic polymers, followed by cellulose esters and then cellulose ethers (Shen et al., 2009). Cellulose acetate films are suitable for injection moulding owing to their tensile strength being similar to polystyrene (Mohanty, Misra, & Hinrichsen, 2000). However, their high sensitivity to moisture means that they are not permanently weather resistant (Shen et al., 2009). This is an obvious impediment to their use for making field netting. Bio-based coatings therefore need to be developed such that the properties of the cellulose polymers are improved without compromising their eco-friendliness.

4.3 Polylactic acid (PLA)

PLA polymers are a family of polyesters derived from the monomer lactic acid (2-hydroxypropionic acid). Since lactic acid exists in both L- and D- optical configurations, PLA is often named, according to its molecular composition, as poly(XY-lactic acid), where X and Y are the respective amounts of L- and D-lactic acid (Auras, 2010). However, since lactic acid produced by the petrochemical route is racemic, while that produced by fermentation is almost exclusively L-lactic acid, the production and purification process used for the lactic acid has a major impact on the properties and the environmental footprint of the PLA produced (Lunt, 1998). Starch and cellulose are the most commonly used feedstocks for PLA production (Sin, Rahmat, & Rahman, 2013). PLA is mostly produced commercially using the ring-open polymerisation process, although two other commercial routes- direct condensation polymerisation, and azeotropic dehydration condensation- exist (Auras, 2010; Drumright, Gruber, & Henton, 2000). Other synthesis methods involving different polymerisation conditions or biosynthesis are under development (Xiao, Wang, Yang, & Gauthier, 2012). The general optical, physical, mechanical and barrier properties of PLA are most similar to PS and PET, and hence PLA has found increasing use in replacing them as a 'green' material (Auras, Singh, & Singh, 2005). Among other advantages, PLA has an average degradation time in the environment of only 6 months to 2 years, as compared to 500-1000 years for PS and polyethylene, and the properties of PLA resins can be tailored for use in a variety of processes and applications by modifying certain molecular parameters (Drumright et al., 2000; Sinclair, 1996). Accordingly, PLA has found a wide range of applications in the domestic, biomedical and engineering sectors (Sin et al., 2013), and with a global production of 370,000 ton per annum in 2011, is one of the most commercially important biopolymers (Lewandowski, 2018). Its production can be expected to increase further due to its application in 3D printing, where its use is preferable to a petroleum-derived polymer like acrylonitrile butadiene styrene (ABS) for lowering environmental impact vis-à-vis conventional manufacturing (Kreiger & Pearce, 2013).

The mechanical properties of PLA compare favourably with those of HDPE, except in terms of water permeability, and PLA can potentially replace both HDPE and PP for making agricultural nets. The short degradation time of PLA mentioned above can, however, be a drawback for this application, necessitating a finetuning of the properties so as to ensure a longer lifespan of the netting. A PLA-lignin composite that can absorb nearly all UV-B and UV-C radiation and up to 80% of UV-A light has been developed (Xie, Hse, Shupe, & Hu, 2015). This material can potentially be used to make UV-absorbing nets.

4.4 Polyhydroxyalkanoates (PHA)

PHAs are thermoplastic or elastomeric polyesters of hydroxyalkanoates that are synthesised by numerous bacteria as intracellular carbon and energy storage compounds (Keshavarz & Roy, 2010; Mozejko-Ciesielska & Kiewisz, 2016). Poly(3-hydroxybutyrate) (PHB) is perhaps the most abundant, and the earliest known, PHA, but more recently reported PHAs are often superior in terms of properties such as elasticity and thermal stability (Anderson & Dawes, 1990; Keshavarz & Roy, 2010). PHAs are very attractive owing to the fact that, due to the extensive range of properties that can be achieved via their chemical modification or blending, they can replace petrochemical polymers in most applications (Verlinden, Hill, Kenward, Williams, & Radecka, 2007). This is in addition to their other advantages in terms of their renewable origin, biocompatibility and biodegradability (Verlinden et al., 2007). A limiting factor has long been their high costs owing to the requirement of growing bacteria or yeast under controlled conditions, and the associated problems of maintaining optimised conditions at an industrial scale (Karthikeyan, Chidambarampadmavathy, Cirés, & Heimann, 2015; Mozejko-Ciesielska & Kiewisz, 2016). Much of the research on PHAs in recent years has therefore focussed on the reduction of their production costs. PHA synthesis in transgenic crops is one solution that has been proposed (Suriyamongkol, Weselake, Narine, Moloney, & Shah, 2007); however, this has been stymied by the fact that plant cells can normally cope with much lower levels of PHA (<10% (w/w) dry wt.) than bacterial cells (~90% (w/w)) (Verlinden et al., 2007). Progress, nevertheless, is being made in synthesising PHA in both C_3 and C_4 plants (Snell, Singh, & Brumbley, 2015). The use of cheaper carbon sources, such as waste frying oil or waste water sludge, as the raw material is another research avenue (Jiang et al., 2016; Pittmann & Steinmetz, 2016). Integrating PHA production into biorefineries and focussing on optimisation of the overall process rather than on individual indicators can also help improve the cost competitiveness of PHAs on a large scale (Dietrich, Dumont, Del Rio, & Orsat, 2017).

PHB can compete with conventional polymers in terms of Young's modulus, tensile strength and impact strength, and especially resembles isotactic propylene (i-PP) in terms of Young's modulus (3.5-4 GPa), melting temperature (175-180 ^{o}C) and tensile strength (40 MPa) (Bregg, 2006; Rieger et al., 2012; van der Walle, de Koning, Weusthuis, & Eggink, 2001). The main drawback of PHB as compared to i-PP (Figure 2) is its brittleness, i.e. low strain elongation. The elongation to break of only 3-8% for PHB is much lower than the 400% for iPP, and this lack of ductility is an obvious disadvantage when it comes to netting applications. However, PHB-based composites can offer substantial environmental benefits in terms of non-renewable energy use and GWP100 (Pietrini, Roes, Patel, & Chiellini, 2007).

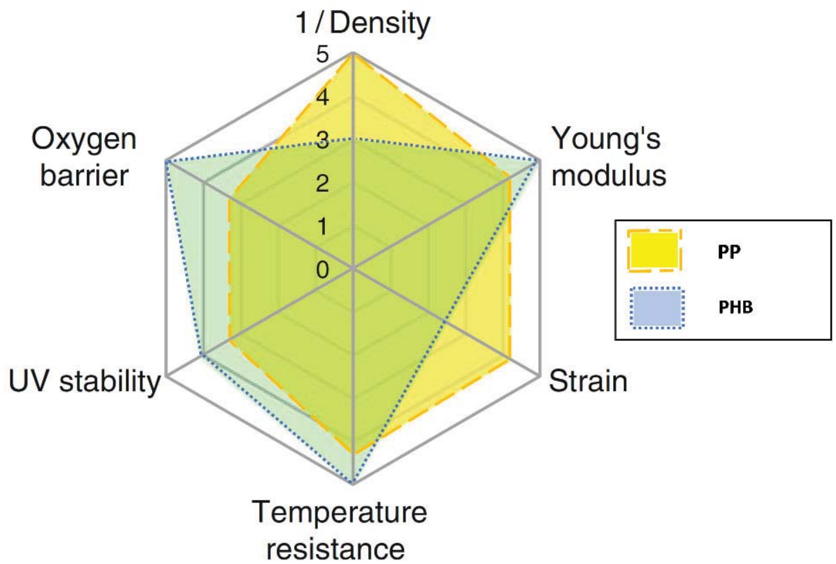

Fig. 2: Qualitative comparison of mechanical properties of Poly(3-hydroxybutyrate) (PHB) and isotactic propylene (i-PP) (adapted by permission from (Rieger et al., 2012))

In recent years, PHA-starch blends have been developed that have mechanical properties comparable to HDPE (Godbole, Gote, Latkar, & Chakrabarti, 2003; Innocentini-Mei, Bartoli, & Baltieri, 2003; Ramsay et al., 1993). The parameters that were similar to HDPE included Young’s modulus (1000-2000 MPa), yield stress (~24 MPa) and strength at break (30-35 MPa). These properties can be modified both by changing the proportion of starch and the specific PHA used. The percentage of starch used can also be altered to control the biodegradability of the blend (Ramsay et al., 1993). It is clear that this holds great promise for the manufacture of agricultural netting, as nets with mechanical properties similar to those of existing HDPE nets can be made while simultaneously adjusting the biodegradability to suit the application in question.

4.5 Bio-polyethylene

With an annual global production of 84 million tonnes in 2014, polyethylene (PE) is the largest volume polymer produced worldwide (Dobbin, 2017). A thermoplastic polymer, PE is composed of only carbon and hydrogen, but these two elements can be combined in various molecular architectures to make a range of products like LDPE, HDPE, linear low density polyethylene (LLDPE), very low density polyethylene (VLDPE), and so forth (R. M. Patel, 2017). Additionally, the properties of PE resins can be changed by altering their degree of crystallinity via copolymerisation with other comonomers. While the vast majority of ethylene, the monomer of PE, made worldwide comes from the steam cracking of petroleum, it can also be made by catalytically dehydrating biomass-derived ethanol or via direct enzymatic synthesis from biomass (Fink, 2017; Morschbacker, 2009). Bio-PE has identical properties to petrochemical PE, and hence can be used in any application where petrochemical PE is currently being used. Given the predominance of HDPE in agriculture net manufacture, it is evident that bio-PE is of great interest in this area, although like other biopolymers, competing on cost continues to be a challenge (Chen & Patel, 2012) .

Similar to bio-based PE, other polymers currently being made from petrochemicals can also be made starting from renewable biomass resources. In some cases, this can involve using the same process and simply changing the origin of the monomer used, such as using biomass-derived ethylene for making PVC (Shen et al., 2009). Alternatively, a new process scheme can be used, such as a proposed scheme utilising 5-hydroxymethylfurfural (HMF) and glycerol to synthesise bio-based PET (Shiramizu & Toste, 2011). Accordingly, bio-based replacements of polytrimethylene terephthalate (PTT), polybutyleneterephthalate (PBT), polybutylene succinate (PBS), polyurethanes (PURs), nylon, etc. have been subjected to intensive research, as well as being produced on a limited scale (M. Patel, Marscheider-Weidemann, Schleich, Hüsing, & Angerer, 2005). The use of bio-based natural polymers like chitin, chitosan, pullulan, collagen, gelatin and alginates is also being trialled for specialised applications (Babu, O'Connor, & Seeram, 2013).

5. Use of biopolymers for the manufacture of exclusion nets

Table 2 summarises the relevant polymer properties for the manufacture of exclusion nets with existing polymers and some candidates for this industry. Prices are only widely available for petro-polymers, as the market for biopolymers is still niche and the prices subject to rapid evolution due to process improvements.

Table 2: Relevant properties of commonly used polymers in the agrotextile industry

Polymer	Water contact angle (°)	Tensile strength (MPa)	Tensile Modulus (MPa)	Elongation at break (%)	Material cost (2017) $(US\ \$\ kg^{-1})$	Density $(g\ cm^{-3})$	Fiber tenacity (cN/tex)	Exclusion net, manufacturers examples	End-of-life disposal	Bio-sourced polymer	
										Availability	Prod. Capacity, 2018 (MT/a)*
HDPE	~80[a]	13-51[a]	500-1100[a]	250-1200[a]	1.11-8.6[b]	0.94-0.97[a]	32-70[a] (PE)	ProtekNet[d], Emis 3310	Well developed recycling	Bio-PE	0.20[f]
PA6†	~60[a]	74-106[a]	570-1200[a, e]	327[a, e]	2.60-11.37[b]	1.06-1.16[a]	40-90[a]	ProtekNet[d], Biothrips®	Developed recycling	PA11, PA12, PA610[94]	0.23[f] (PA grade not specified)
PP	~100[a]	26-32[a]	1700[a]	10-140[a]	1.12-3.56[b]	0.84-0.91[a]	15-60[a]	Agryl, Filbio® [d]	Well developed recycling	Bio-PP	N.A.
PLA	~80[c]	52-72[a]	2700-16000[a]	4-6[a]	1.91-4.77[b]	1.21-1.29[a]	32-36[a]	Filbio® [d]	Marginal recycling, compostable	PLA	0.21[f]
PET	~73[a]	24-41.1[a]	2300[a]	100-250[a]	0.99-2.78[b]	1.3-1.4[a]	25-95[a]	N.A.	Well developed recycling	Bio-PET	0.55[f]
PHB	~88[g]	24-62[a,h]	820[h]	5.8[h]	N.A.	1.17-1.25[a]	N.A.	N.A.	Marginal recycling, compostable	PHB	N.A.

a : Adapted from (Wypych, 2016) b: (Plastics Insight, 2017) c : (Farah, Anderson, & Langer, 2016)
d : The cited brand name includes different polymers for net manufacture e : After conditioning
f : Adapted from (Chinthapalli et al., 2018) g : (Andreotti, Franzoni, & Fabbri, 2018) h : (Monshupanee, Nimdach, & Incharoensakdi, 2016)
N.A. : Not available †: PA6 = Polyamide 6 * MT/a = million tonnes per annum

Although, as seen in Section 2, the use of pest exclusion nets has become fairly common in agriculture worldwide, there has been surprisingly little work done on evaluating the applicability of biopolymers for the manufacture of these nets. Most of the research on the materials used for the nets has so far focussed on improving their durability, UV transmission, porosity, or other properties. Among the limited work that has been done on the use of biopolymers for exclusion netting is a 2004 study that investigated using a starch-based biodegradable film for protecting strawberries in Italy (Scarascia-Mugnozza, Schettini, & Vox, 2004). In this study, the film showed a decrease in transmissivity of PAR over the test period, but otherwise exhibited agronomic results comparable with traditional LDPE films. The publication of several articles looking at the mechanical, radiometric and other properties of starch based biodegradable films shows the high level of interest in them (Briassoulis, 2006; Kapanen, Schettini, Vox, & Itävaara, 2008; Vox & Schettini, 2007). The radiometric properties, field performance and useful lifetime of these films have been found to be on par with LDPE films (Kapanen et al., 2008; Vox & Schettini, 2007). On the other hand, certain mechanical properties such as the elongation at break would need to be improved by optimising the process parameters used in the blow extrusion of these films (Briassoulis, 2006). PLA has also been used to develop agricultural netting, for instance using Lactron, a PLA fibre produced by Kanebo Goshen in Japan (Ashter, 2016).

One reason for the paucity of biopolymer use for agriculture netting may simply be their higher cost (Castellano, Mugnozza, et al., 2008), although it has been argued that if the biopolymer used is biodegradable, then their price becomes comparable to traditional ones when the costs of collection, disposal and recycling are taken into account (Scarascia-Mugnozza et al., 2012) (see Section 7 for a discussion on biopolymer disposal). Another reason may simply be the unavailability of biopolymer nets- as stated in Section 4, biopolymers account for only around 1% of worldwide plastic production, and their utilisation for fabricating exclusion nets has most likely not been considered to be a priority by biopolymer manufacturers.

The BIOAGROTEX project, carried out between 2008-2012, is one of the few large-scale studies on the use of biopolymers for agrotextiles, including netting (BIOAGROTEX, 2012). This project failed to accomplish the application of starch-based thermoplastics owing to their inadequate mechanical properties, but PLA-based formulations could be used for production of non-woven, knitted and woven fabrics. Laboratory and real-life durability testing showed that these fabrics would have an expected life time of at least three to five years. This project led to the commercialisation of PLA nets under the trade name Filbio PLA in Europe (Centexbel, 2014).

When the use of biopolymers for manufacturing exclusion nets is considered, several factors need to be taken into account. One, evidently, is cost. Increasing biopolymers production, coupled with a rise in petroleum prices, is likely to make biopolymers, in general, more cost-competitive, and this will filter down to their use in exclusion netting. If the materials used differ from those used presently only in terms of their origin, such as HDPE made from biomass instead of from crude oil, then other critical parameters, such as durability, UV and PAR transmission, will remain the same, and any concerns regarding them will have to be addressed in a manner similar to present. On the other hand, for novel materials, such as PLA or PHA, it needs to be ensured that their performance is at a level comparable to, or better than, those of existing netting materials. For instance, it has been reported that the elongation at break value of certain starch polymer-polyester blend films can decrease rapidly in field conditions (Briassoulis, 2006). Therefore, laboratory development of optimised materials has to be carried out in conjunction with field testing to ensure that the biopolymer nets perform to a satisfactory level over the long term. Substituting biopolymers for petroleum-derived plastics is also much easier for nascent sectors than ones where conventional plastic use is entrenched, and hence biopolymer pest exclusion netting deserves to be a focal area for both material research and development (R&D) and field deployment.

6. Sustainability of biopolymers

The underlying premise behind recommending the use of biopolymers for fabricating nets has been their greater environment-friendliness as compared to conventional plastics. It is, therefore, apposite to scrutinise biopolymers on this point to ensure that this is genuinely the case.

6.1 Land use for biopolymers

Biopolymers are, by definition, derived from biomass, and the large-scale production of many biopolymers requires the use of crop-based materials. While the use of non-food feedstocks, such as lignocellulosic biomass in place of corn starch, can avoid the diversion of food crops to biopolymer synthesis, this leaves unaddressed concerns about competition with food crops for agricultural land use in a manner similar to biofuel production. In case of biofuels, this issue has been extensively studied in terms of the impact of various development scenarios on cultivated, pasture and forest lands in different parts of the world, with conflicting conclusions arising from differences in the assumptions and methodologies used (Banse et al., 2011; Blanco Fonseca et al., 2010; Cai, Zhang, & Wang, 2011; Danielsen et al., 2009; Fischer et al., 2010; Havlík et al., 2011; Keeney & Hertel, 2009; Lapola et al., 2010; Pimentel et al., 2008; Ravindranath, Sita Lakshmi, Manuvie, & Balachandra, 2011). For instance, the inherent uncertainties regarding technology and scale of biofuel adoption mean that land requirement in 2050 could be estimated to be anywhere between 7% to 45% of the global arable crop land (Murphy, Woods, Black, & McManus, 2011). This is just as true for biopolymers, where the extent of competition for land will depend on, among other factors, the global population growth, food requirements, demand for liquid fuels, and agricultural yields (Colwill, Wright, Rahimifard, & Clegg, 2012). This is before even considering future biopolymer demand, the types of biopolymers that will become prevalent, and the technology that will be used for their manufacture. Despite this uncertainty, it is clear that biopolymer development needs to be geared towards minimising agricultural land use. The use of waste biomass, growing feedstock crops on degraded or non-agricultural land, emphasising resource efficiency during production, and improving end-of-life management have been proposed as ways to reduce agriculture land requirements for biopolymer production (Colwill et al., 2012; Piemonte & Gironi, 2011).

6.2 Carbon neutrality

An allure of biomass-derived polymers is their ostensible carbon neutrality, since the amount of carbon dioxide released at the end of their lifespan is supposed to be the same as that which had been absorbed during photosynthesis by the plants from which the polymer was made. In reality, this is seldom the case. Cultivation of the crop requires fuel for activities such as ploughing, application of agrochemicals and harvesting (Yates & Barlow, 2013). This fuel is usually of fossil origin, and therefore a source of GHG emissions. The manufacture and transport of required materials like fertilisers, herbicides and pesticides is another potential source of GHG emissions. The transport of the crops to the processing plant, their conversion to biopolymers, purification of these biopolymers and their transformation to the end-product, and the conveyance to and the deployment at the place of application of these end products all require the expenditure of energy, and thus have their associated GHG emissions. Wastage occurring at every step also means that the final weight of the end-product is often considerably lesser than the original weight of the biomass collected, another reason why the 'carbon cycle' of biopolymers is not actually a closed loop.

Several studies have been conducted to evaluate the actual emissions of biopolymers vis-à-vis their petrochemical counterparts. The results obtained have varied depending not only the biopolymer in question and the feedstock used for its preparation but also on the methodology used for the calculations. In general, these studies appear to indicate lower lifetime GHG emissions for biopolymers. For instance, a study comparing fossil HDPE with HDPE made from sugar beet and wheat showed approximately a 60% reduction in climate change impact for the bio-based HDPE (Belboom & Léonard, 2016), while another work comparing PLA and petrochemical-PET bottles showed a similar drop in the "cradle-to-grave" climate change impact for the biopolymer (Gironi & Piemonte, 2011). Likewise, the 100-year GWP of PE has been found to be about 50% higher than for PHB, with that of PP being over 80% higher (Harding, Dennis, von Blottnitz, & Harrison, 2007). On the other hand, using the Tool for the Reduction and

Assessment of Chemical and Other Environmental Impacts (TRACI) v2.0 developed by the US Environmental Protection Agency (EPA) (Bare, 2011), and the ecoinvent v2.2 database, Hottle et al. found that the GWP of TPS was comparable to PE and PP, while that of PLA was higher than that of all petroleum-based polymers except for PS (Hottle, Bilec, & Landis, 2013). It must be noted that the tools used to arrive at these conclusions are only based on cradle-to-granule analysis (or cradle-to-gate), and hence only based on the production step of the polymer. In a more recent analysis by the same group, multiple biopolymers are compared in terms of production and disposal, with several end-of-life possibilities available for each type of polymer (compost, landfill or recycling) (Hottle, Bilec, & Landis, 2017). In that analysis, one can note that PLA has a smaller production GWP than petro-sourced PE, but the whole cycle of that polymer (production and end-of-life disposal) is highly variable, and can have an overall GWP impact about 5 times higher than HDPE if that later polymer is completely recycled, as shown in Section 6. Therefore, the impact of the end-of-life disposal has to be considered carefully (see Section 7). It is noticeable that the analysis has also been carried out with the TRACI software, giving conclusions different from the previous study (Hottle et al., 2013). This illustrates the fact that LCA is deeply sensitive to upgrade of the available tools, as long as to the development of the technologies and the available knowledge on it (Talon & Bergmann, 2014).

As mentioned above, the methodologies used to calculate the GWP makes a big difference in the calculated values (Pawelzik et al., 2013; Yates & Barlow, 2013). For instance, the carbon footprint of a polymer can be divided into material and process carbon footprints (Narayan, 2011). The LCA of a polymer, carried out as per ISO 14040, focuses mostly on the process footprint, that is, on the emissions during the conversion of the feedstock into the product, the impact during product use and its ultimate disposal. However, the material carbon footprint of a biomass-derived polymer is essentially zero, since the end-of-life CO_2 emissions comes carbon that had been sequestered a short time (< 10 years) earlier. This means that the overall carbon footprint of a biopolymer, combining the process and material footprints, of PLA may be lower. This intrinsic carbon footprint may be defined as the mass of "old" carbon released at the end of life per 100 kg of the polymer, as determined by a C-14 test, which relies on the absence of C-14 in petrochemical feedstock (Talon, 2014). For example, Ramani calculated the carbon footprint of PLA to be under 400 kg CO_2 released per 100 kg polymer manufactured, as opposed to over 500 kg CO_2 per 100 kg polymer for PE and PET (Narayan, 2011).

The cultivation of the crops required for biopolymer production is also a source of GHG emissions. During cultivation of corn used for PHA synthesis, nitrous oxide (N_2O) is released from the soil to the tune of 10-13 g kg^{-1} (S. Kim & Dale, 2004). Such emissions can be accounted for in LCAs using process-oriented models like Denitrification-Decomposition (DNDC), but this is not commonly done in published studies (M. Guo, Li, Bell, & Murphy, 2012). GHG emissions due to Land Use Changes (LUC) caused by biopolymers crop production are also usually neglected in LCA studies, which also skews results (Piemonte & Gironi, 2011). As a result, while it can be broadly stated that GHG emissions caused by biopolymers are lower than those of petrochemicals, biopolymers are nevertheless not completely carbon-neutral, as the "closed carbon cycle" scheme may imply.

6.3 Non-GHG environmental impact

Reduction in GHG emissions is only one aspect of environment-friendly material production. Other aspects that need to be considered include ozone layer depletion, emission of sulphur dioxide, particulate matter and other air pollutants, terrestrial and freshwater eutrophication, human health, and ecotoxicity (Bare, 2011). It is far from clear that biopolymers are better than conventional plastics with respect to these parameters, with multiple studies showing that they actually do worse on several counts (Belboom & Léonard, 2016; Gironi & Piemonte, 2011; Harding et al., 2007; Hottle et al., 2013; Yates & Barlow, 2013). The process used to produce the polymer also affects the LCA results, meaning that a polymer derived from by-products or wastes and synthesised using clean energy in an optimised fashion will have a better ecological performance in an LCA analysis (Narodoslawsky, 2015). Factors such as the specific end-of-life scenario (Section 7) and the recycled content of the petrochemical polymers they are being compared against will decide if the use of a renewable polymer like starch-polyvinyl alcohol is environmentally advantageous over HDPE, LDPE or PS (M. Guo & Murphy, 2012). Such decisions therefore have to be made on a case-by-case basis. Ultimately, the production of biopolymers is still relatively immature and a work in progress, and future optimisation and process efficiency improvements should lead to improvements in their environment-friendliness, provided that this is rendered a priority.

6.4 Biodegradability

A common misconception related to biopolymers is that they are all biodegradable (Iwata, 2015) . The 'bio-' prefix for biopolymers, as the term is used in this work, merely refers to their origin from biomass, and their biodegradability is not assured. For instance (Figure 3), polysaccharide derivatives with a high degree of substitution may not be biodegradable, while polymers like PE and PET have identical material properties whether they are made from renewable or non-renewable resources, and hence bio-PE and bio-PET are also non-biodegradable (Iwata, 2015). On the other hand, fossil fuel-derived polymers like polycaprolactone (PCL), PBS and polypropiolactone (PPL) are biodegradable (Tokiwa, Calabia, Ugwu, & Aiba, 2009; Tokiwa & Pranamuda, 2005). Occasionally, the biodegradability of a particular polymer is controversial- for instance, cellulose acetate was long considered to be non-biodegradable, but is largely considered to be biodegradable today (Mohanty et al., 2000; Puls, Wilson, & Hölter, 2010). Therefore, while certain biopolymers like PLA and PHA have the dual advantage of being made using renewable resources and biodegradable, the utilisation of others, like bio-PET and bio-PE, need to be evaluated based solely on the benefits of using a renewable feedstock, since problems related to their end-of-life disposal will not disappear simply by changing the feedstock.

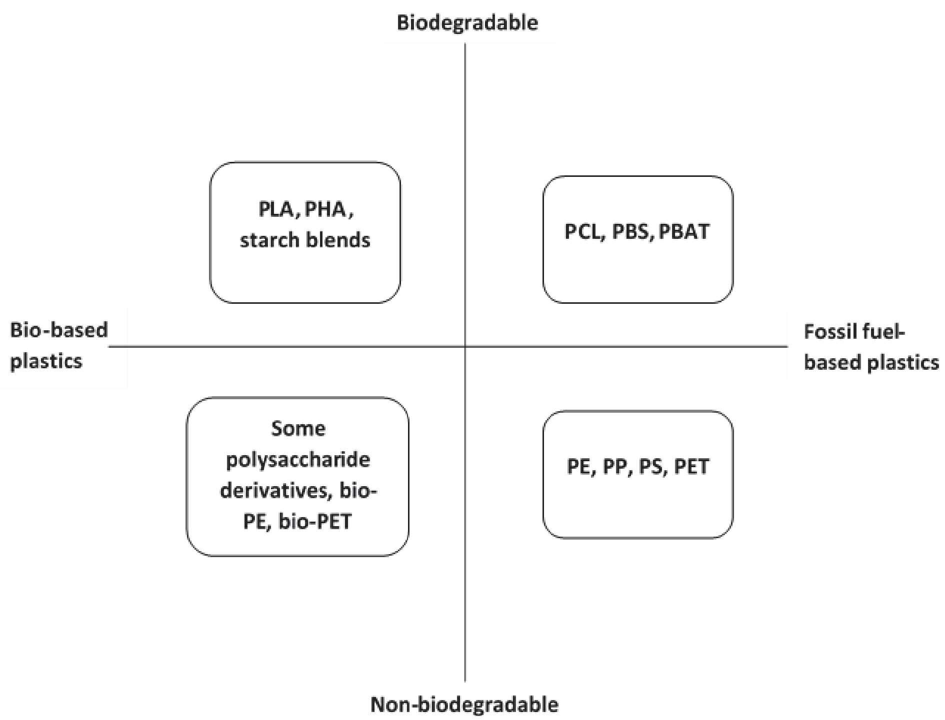

Fig. 3: Classification of plastics according to their feedstock and biodegradability (Iwata, 2015; Philp, Bartsev, Ritchie, Baucher, & Guy, 2013)

Furthermore, even the polymers that are deemed "biodegradable" may not just degrade immediately into carbon dioxide and water in a real-life scenario. The degradation of certain polymers may only be carried out by specific organisms, and hence in the absence of these organisms in the environment, the polymers will not degrade readily. For instance, polyethylene succinate (PES) has been often considered to be a biodegradable polymer (Gan, Abe, & Doi, 2000; Qiu, Ikehara, & Nishi, 2003); however, the degradation of PES is strongly influenced by environmental factors, and moreover, PES-degrading microorganisms are limited in their distribution (Kasuya, Takagi, Ishiwatari, Yoshida, & Doi, 1998; Tokiwa et al., 2009). In ocean water, the rate of biodegradation of most polymers is slowed down considerably, and hence the problem of marine plastic pollution may not be solved by a switch to biodegradable polymers (Kasuya et al., 1998; Philp et al., 2013). If inserted into landfills, the biopolymers may be subjected to anaerobic digestion, releasing methane, which has around 85 times the GWP of CO_2 over a 20-year horizon (Khoo & Tan, 2010; Myhre, 2013). In other cases, the plastics may not biodegrade in a landfill at all

(Mülhaupt, 2013; Philp et al., 2013). The partial biodegradation of polymers into micro- and nanoparticles can also lead to health problems, such as respiratory diseases upon inhalation, while the possible production of water-soluble and toxic metabolites during biodegradation can lead to groundwater pollution (Mülhaupt, 2013).

In any case, whether biodegradability is indeed a positive attribute for agricultural netting material is debatable. Field exposure inherently entails extensive exposure to UV-radiation, high levels of moisture, wind, and other environmental agents. In addition, it often involves close contact with soil, microorganisms and agrochemicals. All this means that a certain degree of stability is required for a netting material to be practical, as a biodegradable material that has a field life of the order of months cannot conceivably be used. Durability may therefore trump biodegradability in desirability, and this criterion has to be considered for new material biodegradable material development.

Figure 4 displays the results of (Hottle et al., 2017), where an extensive set of data has been presented in terms of end-of-life disposal and environmental impact for four polymers discussed in Section 4 — PLA, TPS, HDPE and bio-HDPE. Three categories have been selected to illustrate the variability of LCA results depending on the implemented scenarios: GWP, Ecotoxicity and fossil fuel depletion. GWP quantifies the cradle-to-grave effect on climate change of a polymer. The ecotoxicity section helps appreciate the damage caused in the different media (air, soil and water) by organic or inorganic substances used and released during the fabrication, processing and degradation of the studied material. Fossil fuel depletion expresses the relative quantity of fossil resources consumed (or avoided in case of recycled material) upon the material's fabrication and end-of-life management. One can note the drastic environmental impact variation depending on the used method for end-of-life management. For PLA, composting results in lower GWP than landfilling for the 'high' scenario, whereas in the 'low' scenario the trend is reversed, due to differences in the management of the degradation products. However, the comparison between HDPE and PLA in Figure 4 shows that depending on the end-of-life management, the biopolymer can have a significantly higher GWP impact than the petro-sourced HDPE. The issue of what happens to bio-based polymer nets at the end of their useful life is hence of great importance, and this is discussed in Section 7.

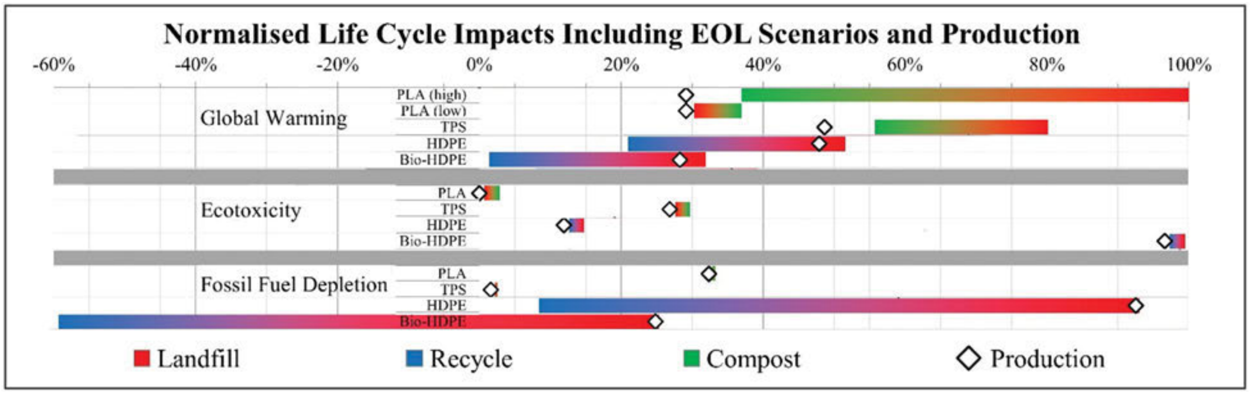

Fig. 4: Life Cycle Analysis (LCA) outcomes with Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) v2.1 (Bare, Young, Qam, Hopton, & Chief, 2012) for the environmental impact categories, adapted with permission (from (Hottle et al., 2017)).

The values in Fig. 4 have been normalised to the highest impact value for each category. Shaded bars represent the range of values obtained when a set of technology is implemented, as indicated by the colour. The ends of the bars mean that 100% of the polymer has been treated with this technology. In the original work, LDPE was shown to reach 100% in the Fossil Fuel Depletion category, but it is not represented here in order to focus on polymers more relevant to agricultural netting, and so no polymer presented here reaches 100% in this category. Across the bars, the distribution of each option is proportional to the position (halfway of the bar means half the quantity is treated with one technology, the second half with the other). Polylactic acid (PLA) has two scenarios in the Global Warming category, a high (no gas capture in the landfill, degradation) and a low (no degradation). For other categories, less than 1% difference was found for both scenarios, so only the values for the low scenario were included.

7. End-of-life disposal of biopolymers

The concerns regarding biodegradability mentioned in Section 6.4 are not specific to biopolymers, but they do illustrate the need for well-thought-out end-of-life disposal plans for these polymers. Current agricultural nets have an average lifespan of four to six years (Castellano, Mugnozza, et al., 2008), with some lasting up to ten years (Chouinard et al., 2016), and biopolymer nets may have similar lifespans. It is therefore imperative to clarify the best practice end-of-life protocols for biopolymer nets in order to prevent their accumulation in fields or in landfills after use in a manner similar to existing nets.

As per ASTM D5033, recycling of plastic waste can be grouped into four categories (ASTM, 2000). These are (1) primary recycling, which refers to mechanical reprocessing into a product with equivalent properties; (2) secondary recycling, or mechanical reprocessing into a product with properties different to the original; (3) tertiary recycling, which is the production of basic chemicals or fuels from the plastic; and (4) quaternary recycling, or recovery of the energy content of the scrap plastic (ASTM, 2000; Hopewell, Dvorak, & Kosior, 2009). For dry biodegradable polymeric material, mechanical recycling is the best option in terms of energy savings and resources depletion impacts (Piemonte, 2011; Rossi et al., 2015). This process, however, has the drawback of the product quality being lowered after every recycling step, leading to a drop in its market value and its being directed towards downgraded applications (Badia, Gil-Castell, & Ribes-Greus, 2017; Soroudi & Jakubowicz, 2013). The sensitivity of this method to contamination is also an issue (Soroudi & Jakubowicz, 2013). Also, while mechanical recycling is widespread for HDPE and PET, for these systems to be used for biopolymers, they need to either be completely interchangeable with the existing resins, or be produced in quantities large enough to justify their own recycling system (Cornell, 2007). Bio-based versions of petrochemical polymers, like bio-PE or bio-PET, may therefore be more suited to mechanical recycling than other biopolymers that have properties different from existing polymers and are produced in quantities too limited to merit their own recycling system.

Another recycling method that can be used for biopolymers is chemical recycling. Here, the polymeric material is broken down into monomers, which are subsequently repolymerised by feeding into the polymerisation reactor (Soroudi & Jakubowicz, 2013). For instance, PHAs can be chemically recycled using enzymes (Matsumura, 2002) or alkali earth compounds (Ariffin, Nishida, Hassan, & Shirai, 2010) as catalysts. However, as compared to mechanical recycling, chemical recycling is costlier, more energy intensive, has a more complicated process, and is only applicable for certain biopolymers (Soroudi & Jakubowicz, 2013). For biopolymers that are difficult to mechanically recycle, such as PLA, chemical recycling nevertheless is a promising avenue of research (Soroudi & Jakubowicz, 2013). Certain hybrid approaches involving monomer recovery from methods classified as energetic valorisation are discussed below.

In recent years, biological recycling has been proposed as another method for recycling plastics. This has the advantage of being able to tackle mixed plastic waste which may not be easily recycled using other means. For example, a single PVC bottle among 100,000 PET bottles can ruin the entire melt of material during conventional recycling (Koshti, Mehta, & Samarth, 2018). Enzymatic recycling, in contrast, can selectively depolymerise plastics. The bacterium *Ideonella sakaiensis* 201-F6, for instance, can produce enzymes capable of converting PET into its two constituent monomers terephthalic acid and ethylene glycol (Yoshida et al., 2016). The enzyme secreted by this organism has been shown to also be effective on the biopolymer polyethylene-2,5-furandicarboxylate (PEF) (Austin et al., 2018). PLA can similarly be enzymatically depolymerised to L-lactic acid by *Amycolatopsis orientalis* (Jarerat, Tokiwa, & Tanaka, 2006). This shows that biological recycling is a future possibility for biopolymers.

Beyond recycling, an option for end-of-life biopolymer disposal is their energetic valorisation, via methods such as incineration, pyrolysis or gasification (Badia et al., 2017; Rossi et al., 2015). Since the energy content of biopolymers is similar to that of conventional plastics, there are no technical barriers to their utilisation in energy recovery processes (Müller et al., 2014). From an environmental standpoint, energy recovery is considered to be inferior to recycling, but has the advantage of being less reliant on proper sorting mechanisms (Müller et al., 2014; Piemonte, 2011; Rossi et al., 2015). Therefore, it is an option if recycling fails due to economic or other considerations (Al-Salem, Lettieri, & Baeyens, 2009). In addition to energy recovery, pyrolysis and gasification can also be used for chemical synthesis. The bio-oil produced in pyrolysis is a promising source of valuable organic chemicals such as phenolic compounds (Fu, Farag, Chaouki, & Jessop, 2014; Mukherjee, Das, & Minu, 2014). In case of plastic disposal, it can even be a method of chemical recycling. For instance, PS can be reverse-polymerised by polymerise to yield styrene, which can be reused for PS synthesis (Achilias, Kanellopoulou, Megalokonomos, Antonakou, & Lappas, 2007; Hussain, Khan, & Hussain, 2010; Leclerc, Doucet, & Chaouki, 2018; Undri, Frediani, Rosi, & Frediani, 2014). Similarly, syngas from gasification can be converted into a range of hydrocarbons using the Fisher-Tropsch synthesis (Kamm, 2007).

Finally, certain biopolymers, such as starch-based polymers, are compostable (Kale et al., 2007; Song, Murphy, Narayan, & Davies, 2009). Via composting, a polymer can be converted into soil amendment products. To be deemed compostable, biodegradable polymer needs to pass additional tests, such as those defined in ASTM standard D6400 or ISO 17088. Among the major advantages of composting biopolymers is the relative lack of cleaning and sorting equipment required, and the fact that they can be converted readily into soil amendment additive in commercial or even home composting systems (Kale et al., 2007; Song et al., 2009). This means that composting is generally less expensive than processes like pyrolysis for biopolymer disposal (Niaounakis, 2013). In terms of environmental impact, though, they are considered inferior to both recycling and energetic valorisation, since on composting, CO_2 is released without the energy recovery that occurs during incineration (Finnveden, Bjorklund, Reich, Eriksson, & Sorbom, 2007; Piemonte, 2011; Rossi et al., 2015; Soroudi & Jakubowicz, 2013). As per EN 13432 standards, at least 90% of a compostable material needs to be broken down into CO_2 biologically within six months (European Union, 2000). This means that compostable materials release CO_2 within a short window following the end of the product life, which can be reflected in high GWP values in LCA studies. An LCA of PLA, for instance, found that industrial composting would over a 100 year horizon lead to net CO_2 equivalent emissions > 1.5 kg per kg of material, as opposed to around 1 kg CO_2 equivalent for anaerobic digestion and municipal incineration, and negative emissions of 0.5 kg CO_2 equivalent for mechanical recycling (Rossi et al., 2015). The use of the compost can lead to the long-term binding of carbon in the soil, for instance if used as a substitute for peat in soil improvement. Thus, the end-use of the compost, and how this is accounted for in an LCA, can make a difference between significant GHG savings and net emissions

(Boldrin, Andersen, Moller, Christensen, & Favoino, 2009). The method of composting itself may also play a part in this regard. Home composting, carried out at ambient temperatures, potentially produces lower GHG emissions than incineration. Industrial composting, on the other hand, uses temperatures of 50-60 ^{o}C, and generally has higher methane, volatile organic compound and nitrous oxide emissions. Therefore, industrial composting can have a significantly higher carbon footprint and negative environmental impact than home composting (Hermann, Debeer, De Wilde, Blok, & Patel, 2011; Martinez-Blanco et al., 2010). However, industrial composting is more versatile in terms of the feedstock it can accept, being capable of handle polymers like PLA that do not degrade in home compost systems (Hermann et al., 2011).

Biopolymers that can be composted, rather than merely biodegraded, may have other advantages, such as degrading much more rapidly than other polymers in marine environments (O'Brine & Thompson, 2010), or reducing ammonia emissions during composting of organic waste (Nakasaki, Ohtaki, & Takano, 2000). It has also been suggested that instead of being composted conventionally, they could be fermented to produce lactic acid for use in industrial applications including the synthesis of PLA (Accinelli, Sacca, Mencarelli, & Vicari, 2012). Similarly, plastics containing ester bonds can also be anaerobically converted into ethanol, organic acids, methane and other products (Tokiwa, Iwamoto, Koyama, Kataoka, & Nishida, 1992).

The addition of compounds such as ethylene vinyl acetate (EVA), carbon black, metal oxides and HALS adds another dimension to the recycling of biopolymer nets. The addition of pigments may not affect the recyclability of the material technically but might produce a less marketable recyclate (Briassoulis, Hiskakis, Babou, Antiohos, & Papadi, 2012). Occasionally, the additives may actually improve the properties of the recycled material-for example, EVA can facilitate recycling by increasing the Melt Flow Index (MFI), which is an industrial determinant of polymer quality (Briassoulis et al., 2012; Ferg & Bolo, 2013; Picuno & Sica, 2004). Likewise, since UV radiation exposure is a major factor causing plastic to degrade and becoming unsuitable for recycling, UV stabilisers may indirectly aid recyclability. On the other hand, pro-oxidants and other additives that aim to hasten plastic degradability adversely affect their recyclability. Similarly, the addition of starch to LDPE can lower the MFI value (Pedroso & Rosa, 2005). A final factor is that contaminants from field deployment, such as agrochemicals, soil, metals, etc. can also hamper recycling (Sica, Picuno, & Mugnozza, 2008). The development and implementation of a set of technical standards, specifying the contamination, composition and physical and degradation characteristics of the plastics to be recycled, is thus necessary. This can transform agricultural plastic waste into a labelled, freely tradable commodity, thereby enhancing its valorisation (Briassoulis, Hiskakis, & Babou, 2013).

8. Conclusions

The use of exclusion netting for pest management in agriculture has become more widespread in recent years, but still remains a fledgling alternative to the use of pesticides. It is understandable, therefore, that the use of biopolymers, which are themselves still under development, for fabricating these nets is almost untested at this point. This can be viewed as an opportunity, since the biopolymers can at this nascent stage be developed so as to meet both the requirements of agricultural netting and environmental considerations at the same time.

The following list highlights the major pathways for developing alternative crop protection strategies involving biopolymers:

- Improve the relevant properties of the biopolymers (toughness, life-time, etc)
- Improve the end-of-life management of the material
- Reduce the fabrication costs of the biopolymers
- Assess the field viability of the biopolymer exclusion nets
- Spread the knowledge of this type of IPM method

Bio-HDPE, PLA and PHA may be the most promising options in the near future for fabricating exclusion netting based on criteria such as cost and mechanical properties. However, it is likely that a single biopolymer will not be able to meet all possible requirements, which may in any event sometimes be at odds with each other. For instance, a net should be durable, while also being biodegradable or even compostable; it should be porous enough to facilitate ventilation while being able to prevent the entry of small insects; it should obstruct UV radiation while permitting PAR to pass through, and so on. Rather than merely seeking to meet the standards of present-day nets, which are primarily made of HDPE, biopolymers nets can therefore be developed so as to have better performance characteristics at comparable costs. For this to happen, new biomaterials customised to meet specific requirements would have to be developed and then tested in fields, with the feedback from these tests being used to finetune the properties of the materials. All this needs to be done while ensuring that the ultimate goal of environment-friendliness is not compromised, so that biopolymer exclusion nets become a mainstream method for reducing the ecological footprint of the agricultural sector in the years to come.

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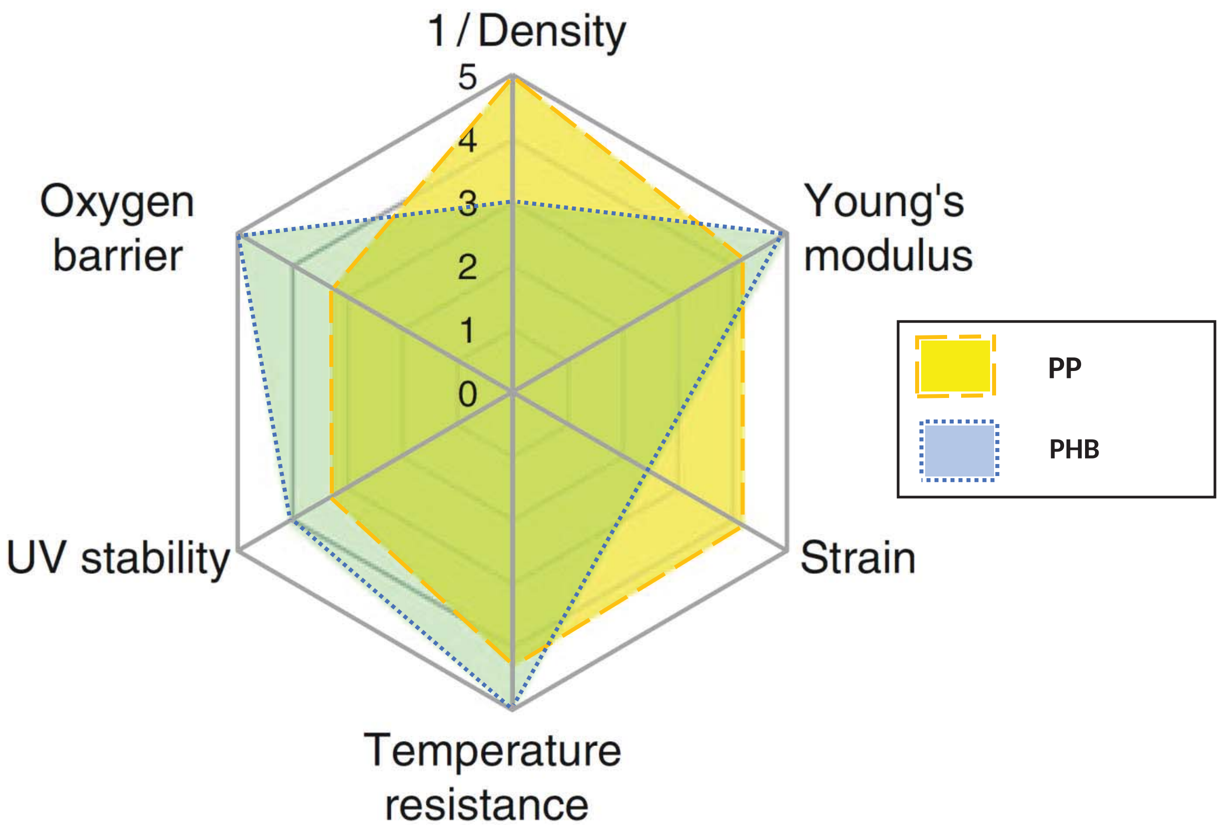
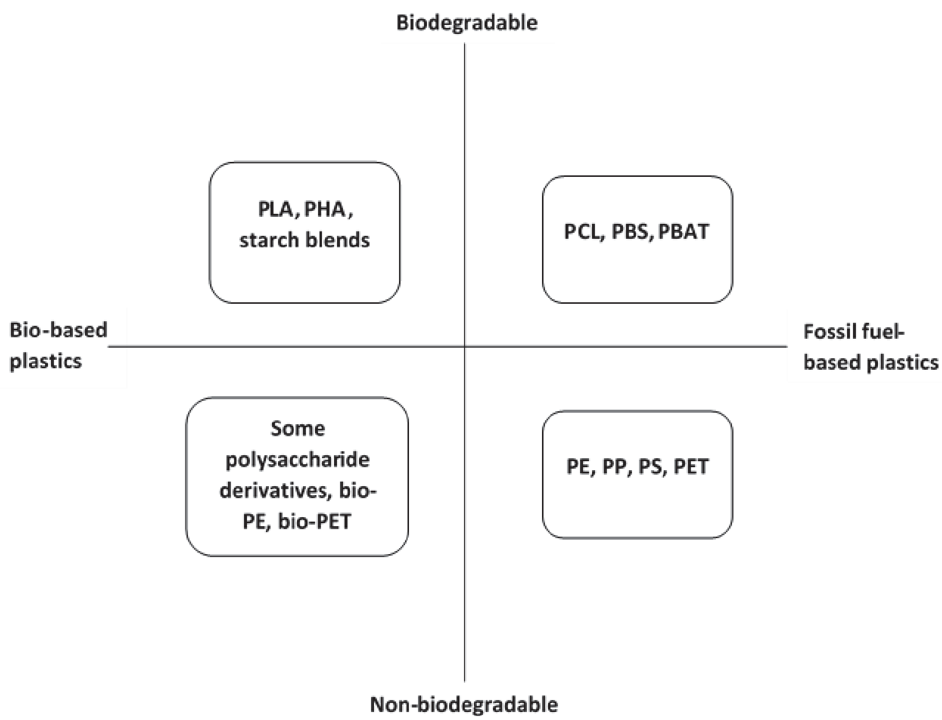
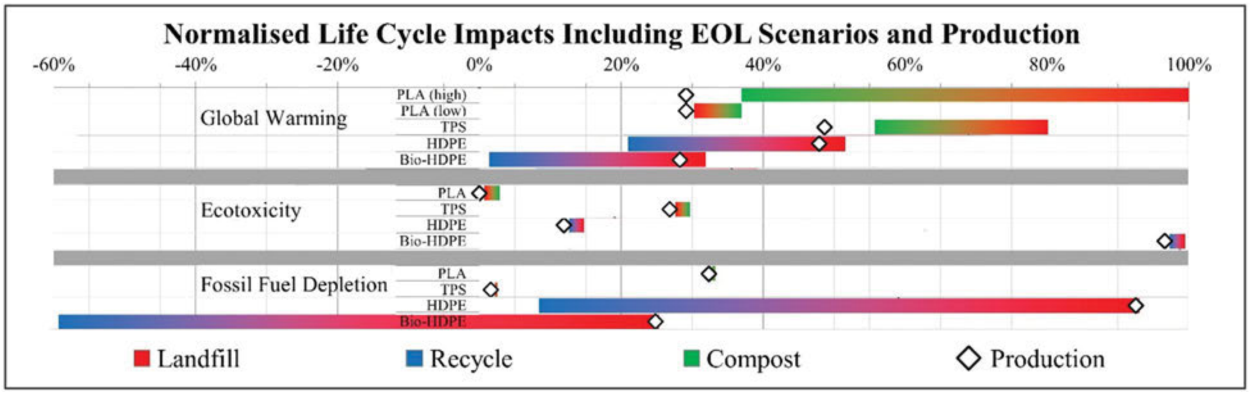
A
B


1 / Density
5
4
3
2
1
0
Young's
modulus
Strain
Temperature
resistance
UV stability
Oxygen
barrier
PP
PHB


Biodegradable
PLA, PHA, starch blends
PCL, PBS, PBAT
Bio-based plastics
Fossil fuel-based plastics
Some polysaccharide derivatives, bio-PE, bio-PET
PE, PP, PS, PET
Non-biodegradable



Normalised Life Cycle Impacts Including EOL Scenarios and Production
-60%
-40%
-20%
0%
20%
40%
60%
80%
100%
Global Warming
PLA (high)
PLA (low)
TPS
HDPE
Bio-HDPE
Ecotoxicity
PLA
TPS
HDPE
Bio-HDPE
Fossil Fuel Depletion
PLA
TPS
HDPE
Bio-HDPE
Landfill
Recycle
Compost
Production