**A Mini Review**

# Bio-innovation of new-generation natural fibrous materials in the footwear industry: Current state-of-the-art and sustainability panorama

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## ABSTRACT

This present paper provides an overview of recent research advances in production technologies towards sustainable development, investigated in the footwear industry as alternatives to conventional fashion fabrics. The current state of the footwear industry as a major stakeholder in the fashion sector is discussed, its footprints on the environment, and key developments on materials for the footwear and other fashion apparels are highlighted. Lastly, the review discusses recent research developed alternatives of leather-like materials from nature, with special focus on sustainability and material performance aspects as well as challenges and limitations in terms of industrial scalability and market potential.

## KEYWORDS

Sustainable leather**;** Agro-derived fiber**;** Footwear**;** Biobased fabrics**;** Fashion industry

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## Introduction

Footwear is one of the major sectors in the fashion industry that is labor-intensive with a high number of shoes products and consumers. From high production capacity to the large consumers' market and with non-definitive details on how to dispose or recycle the used products, two major harmful stage are inevitable. This includes environmental hazards and health risks potential for laborers (Milly 2019; Debnath 2016). For example, the processing of animal hides into leather and assembly in the footwear industry are related with health and safety issues such as usage of chemicals for tanning. These chemicals are then discharge into the surrounding which in tend negatively imparts our environment (Dixit et al. 2015). However, the footwear terminology is a vast definition for products made from many varying materials such as leather, rubber, ropes and wood, which are attributed with different hazards ranging from toxic chemicals during leather fabrication to toxins in glues and plastics (Polese et al. 2019). In addition, the use of leather from both animal hides and synthetic polymers (such as polyurethane (PU) and polyvinyl chloride (PVC)) in the production of footwear products exist as old processing technologies for several decades and even centuries (Nam and Lee 2019a). Nevertheless, the increasing environmental hazards of these produced materials over recent years has arisen major concerns towards the issue of sustainability. This has rendered the global footwear market a no stranger to the issue of sustainability and has gradually drifted the global market towards eco-friendly products particularly in the fashion industry. This paradigm has created a new trend in the fashion sector by slowly changing consumers' perspective towards eco-friendly products (Rathinamoorthy 2019).

Nowadays, large quantities of unexploited materials classified as waste are majorly produced from the agro and food-processing sectors, which includes dairy whey, fruit peels, plant leaves etc. These wastes termed as bio-wastes or biomass have demonstrated wide end-application in the fashion industry (Samanta, Basak, and Chattopadhyay 2015). Moreover, the markets for vegan food has gradually increased over the years, which also implies a growing market for other vegan consumables, such as footwear and textile. These natural based products no longer reside on the margins of the market society since most producers in the footwear industries think of themselves as fashion-conscious consumers. Therefore, the shift towards natural materials derived from plants to produce footwear products makes the system more sustainable and eco-friendlier. Compared to conventional synthetic leather fashion materials from PU and PVC that have raised concern as

regards to their environmental impact due to their long or less biodegradability and are not easily recyclable by any major recycling technique (Ramesh, Palanikumar, and Reddy 2017).

This review provides a short discussion on current research progress of agro-derived fibers/biomass towards the production of sustainable fashion products particularly in the footwear industry. There exists a vast list of unexplored agro-derived fibers with lesser research works on the development of improve consumable end-product performance in the footwear industry. Agro-derived fibers possess huge unexplored sources with possible commercial market and require to be given more attention. In addition, this review discusses recent innovations, challenges and limitations of agro-derived fibers and their promising applications towards green footwear products.

**Economic importance of the footwear industry**

In today's global yet very competitive economy, the fashion sector plays as a major stakeholder in the world market. In 2016, the footwear industry producing capacity surpassed 23 billion pairs of shoes (Kohan et al. 2019). Today, the largest producers and exporters of footwears are based in Asia with over 80% of the global market. China stands as the main manufacturer accounting for almost 2/3$^{rd}$ of shoes sold globally, with a vast variety of designs and United States as their main consumer. In addition, statistics show that approximately 40% of leather shoes are produced in China, followed by 6% in Italy, 6% in Mexico, 4% in India and 4% in Brazil. Other minor producers includes Vietnam, Pakistan, Turkey, Indonesia and Bangladesh (Muller 2018). This makes Asia the top player in the global shoe business. On the other hand, 90% of European production is mostly consumed in Europe with top producing countries as of 2015, which includes Italy, France, Germany, Spain, Portugal, Belgium, United Kingdom, Romania, Croatia and Greece (Mihai et al. 2016). According to statistics, global leather trade on animal hides to finished products over the last decade has been estimated at US$77.5 billion in 2010 and US$91.2 billion between the years of 2013–2018 (Tony Sekulich 2019). The footwear industry in Europe accounts for 41% of the total leather worth, which is the largest market in the fashion sector. But with the increase in the fight against animal cruelty and the strict laws governing the production of real leather, synthetic alternatives from polyurethane (PU) and polyvinyl chloride (PVC) have been extensively explored and developed for usage in areas such as footwear, furniture and automotive.

Recently, the synthetic leather materials possess a global market worth of US$22 billion in 2015 and is predicted to reach US$85 billion by 2025 (Cao et al. 2014; Garcia and Prieto 2019). However, increasing environmental hazards has become a major problem, leading to the development of new leather alternatives. This trend has pushed major top 10 footwear manufacturers including; Nike (revenue: US$36.3 billion), Adidas (revenue: US$24 billion), Kering (revenue: US$15.25 billion), VF Corporation (revenue: US$12.3 billion), Skechers (revenue: US$4.6 billion), New Balance (revenue: US$4 billion), Asics (revenue: US$3.5 billion), Burberry (revenue: US$3 billion), Fila (revenue: US$2.95 billion) and Bata (revenue: US$2 billion) developing interest towards agro-derived/vegan alternatives (Tony Sekulich 2019). Consequently, promoting environmental awareness of the need for the usage of sustainable materials. For example, Nike and Adidas in corporation with the have recently been developing eco-leather materials from agro-derived fibers blended with vegetable (UDaily 2014).

**Sources and features of agro-derived fibers**

Agro-derived fibers are hair-like threads isolated directly from plants and have been used for centuries, famous to consumers who are health conscious, applying these fibers in different fields such as; construction, textile, pulp and paper, food and furniture (Kicinska-Jakubowska, Bogacz, and Zimniewska 2012). But over recent years, there has been a tremendous increase in the use of agro-derived fibers for the fabrication of sustainable and eco-friendly fashion products such as footwears, bags, textile and apparels (Ramesh, Palanikumar, and Reddy 2017). Agro-derived fibers have demonstrated to be a new generation type of renewable sources and reinforcement matrix for the production of fashion product such as footwears. Attributed with properties such as ready availability, low density, cost-effective and good mechanical integrity, depicts them attractive components in the fashion industry (Muthu and Gardetti 2016). Common agro-derived fibers have been categorized according to their origin and plant derivatives as represented in **Figure 1**. **Bast/stem fiber** is generally extracted from the most outer layer of plant stems through biological or chemical degradation processes. The fibers are typically long with high mechanical strength and are used in making bags, textile, ropes, etc (Yu, Wang, and Wang 2019). **Leaf fibers** on the other hand, are coarse and rigid fibers isolated from plant leaves mainly be scraping after a retting or mechanical process. The fibers are of relative high strength and are commonly applied for producing woven ropes, carpets, mats, etc (Hulle, Kadole, and Katkar 2015b). **Fruit/Seed fibers** are produced from the outer shell of fruits such as the husk of coconuts. These fibers are

characterized with light weight, tough, and mainly use for fabricating textile, insulator materials, upholstery, mattress products, brushes, etc (Chauhan and Arya 2018). Another class of agro-derived fibers are the **stalk fibers**, which are extracted from the stalks of plants. Since they do not possess high mechanical integrity, they have found suitable application in the paper and pulp industries (Daud et al. 2016). Lastly, are the **wood fibers** produced from variety of trees and the fibers are commonly classified as softwood and hardwood. The principal difference is the softwood fibers are longer than the hardwood fibers in dimensions (Dai and Fan 2014).

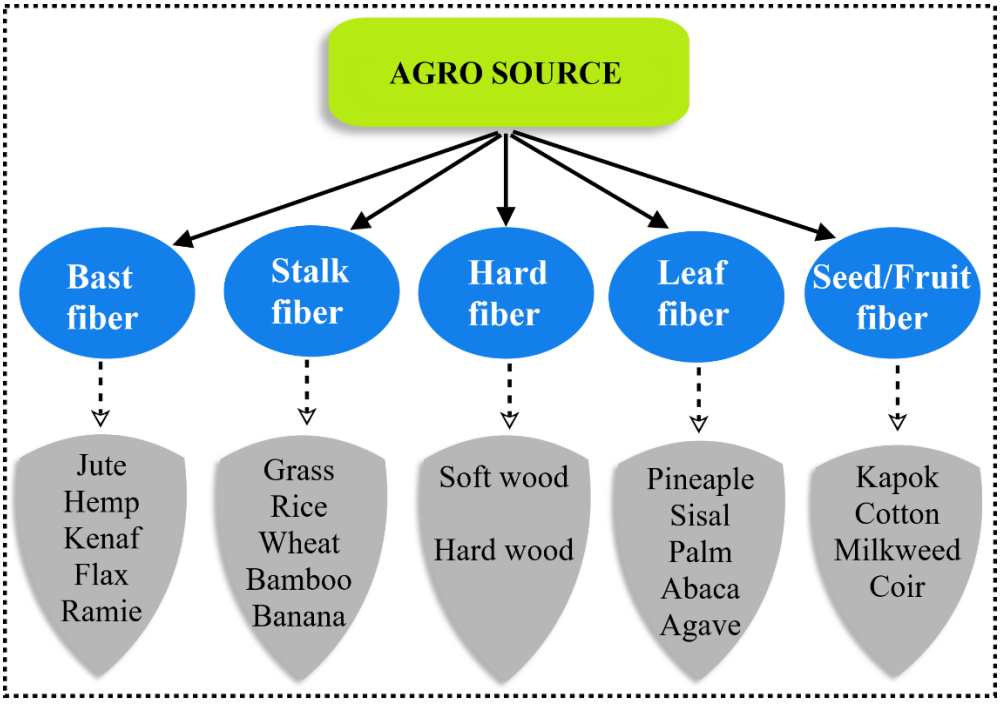


**Figure 1.** Schematic illustration of the sources for agro-derived fibers. Reproduced with permission from (Kumar et al. 2019; Djafari Petroudy 2017; Ramesh, Palanikumar, and Reddy 2017).

The chemo-mechanical constituents of agro-derived fiber structure are moderately complex. **Table 1** outlines the chemical as well as mechanical properties of some common agro-derived fibers from nature. It is well known that natural fibers are basically a rigid, crystalline cellulose reinforced amorphous lignin and/or hemicelluloses with pectin and others in the matrix. Most agro-derived fibers with the exception of cotton, are mainly made of cellulose, hemicelluloses, lignin, pectin and some water-soluble substance.

**Table 1.** Chemical and mechanical features of some common agro-derived fibers (Latif et al. 2019; Kumar et al. 2019; Celino et al. 2014; Hulle, Kadole, and Katkar 2015a).

| **Fibers** | **Major chemical components (%)** | | | | **Mechanical properties** | | | **Moisture uptake (%)** |
|---|---|---|---|---|---|---|---|---|
| | *Cellulose* | *Hemicellulose* | *Lignin* | *Pectin* | *Tensile strength (MPa)* | *Elastic modulus (GPa)* | *Elongation %* | |
| Jute | 45–72 | 12–21 | 0.2–26 | 0.2–12 | 385–850 | 9–55 | 1–2 | 10–13 |
| Hemp | 55–80 | 12–22 | 3–13 | 1–3 | 285–1750 | 14–70 | 0.8–4 | 6–12 |
| Kenaf | 30–55 | 18–24 | 8–21 | 3–9 | 223–1200 | 11–60 | 1–4 | 16-18 |
| Flax | 43–71 | 16–21 | 2–23 | 1.8–3 | 340–1600 | 25–81 | 1–3 | 7–12 |
| Ramie | 68–91 | 5–17 | 0.5–1 | 1.5-2.5 | 200–1000 | 41–130 | 1–4 | 7.5–17 |
| Bamboo | 26–75 | 13–73 | 10–31 | 0.3-1 | 140-230 | 11-17 | / | 10-12 |
| Banana | 48–60 | 10–16 | 14–22 | 2–4 | 711–789 | 4–33 | 2–4 | 2–3 |
| Agave | 68-80 | 13-16 | 5-17 | / | 110-140 | 1.3-2 | 6-8 | 7-10 |
| Coir | 40-50 | 0.2-0.5 | 43-47 | 3-5 | 131-175 | 4-6 | 15-40 | 12-14 |
| Pineapple | 55–75 | 78-85 | 4–10 | 0.8-1.5 | 150-1600 | 11–82 | 2-3 | / |
| Sisal | 45–80 | 10–25 | 7–15 | 0.8–10 | 400–700 | 9–40 | 2–15 | 10–22 |
| Palm | 43–65 | 17–34 | 13–25 | / | 50–400 | 0.6–9 | 4–18 | / |
| Abaca | 56–63 | 15–17 | 7–13 | 0.3–1 | 430–820 | 31–34 | 1.2–1.5 | 5–10 |
| Kapok | 13-20 | / | / | / | 90-95 | 3-5 | 1-2 | 9-11 |
| Cotton | 83–90 | 1–6 | 0.7–29 | 0–6 | 200–800 | 5–15 | 2–12 | 7–20 |

## New-generation sustainable sources

### *Agro and food wastes*

Several researchers have continuously investigated the potentials of converting wastes from the agro and food sectors (**Figure 2**) as sustainable sources of raw materials for the footwear and other apparel manufacture and development into different eco-friendly fabrics. By modifying fruit residues from juice and pulp extract from vegetables, has unveiled an unlimited supply source of raw materials. A good example includes the use of over 700 million tons of Sicilian orange juice industry waste by Orange Fiber S.R.L. in Catania, Italy to produce what is assert as sustainable fiber. In essence, cellulose is isolated from the orange fruit waste and then processed to yarn for the use in the manufacture of knitted and woven materials (Rafiq et al. 2018; Orange Fiber S.R.L. 2015). Another example involves the use of waste pineapple leaves of post agro-harvest in the Philippines by the company Pinatex® to process and extract fibers for the manufacture of footwears and other fashion fabrics in Spain (Dan and Mez 2019). Additionally, seafood shells as waste in the food industry has been explored as a large potential source for the extraction of chitin, which has been deacetylated to chitosan that is well known to possess a wide range of applications.

In the footwear and other fashion sector, this extraction biopolymer has been spun into fiber using the electrospinning technique to process fashion fabrics. For example, this fiber has been blended with some other special commercial fibers to produce yarn in order to design Crabyon© (SwicoFil 2018).

***Microbes and fungi***

Fashion researchers in the field of sustainable development have plunge into innovative design of natural based materials for application in the footwear and other apparels sectors by investigating the potentials of using microbes and fungi (**Figure 2**). Processing technologies using mycelium of mushroom has been recently explored under control conditions to fabricated 3D material assemblies for possible usage areas such as footwear, textile, furniture and architecture. With companies such as Ecovative Design LLC (Green Island, USA) and MycoWorks (San Francisco, CA, USA), mycelium has been growth and processed by binding with other organic components to produce materials with similar appearance to leather (Ecovative Design 2019b; MycoWorks 2017a). On the other hand, the naturally occurring biopolymer cellulose has been widely prepared via biosynthesis pathways using *Gluconacetobacter* bacteria species commonly present in spoiled fruits (Ngwabebhoh and Yildiz 2019; Lin et al. 2013). In comparison to plant cellulose which require chemo-mechanical processes for extraction, bacterial cellulose (BC) contains higher crystallinity with improved features such as tensile strength and high water uptake (Jozala et al. 2016; Xue, Mou, and Xiao 2017). This fascinating biopolymer over recent years has gradually demonstrated some significant breakthrough innovations in the fashion industry. A research study among others by Lee et al. have extensively explore the production of bacterial cellulose through a medium of symbiotic culture of bacteria and yeast (SCOBY) generating gel-like material sheets commonly referred to as “vegetable leather” (Nam and Lee 2019b; Purcell et al. 2017). However, the material has proven to be highly hydrophilic in nature with increasing humidity and cannot washed domestically. Nonetheless, researchers have gradually continued research in field towards possibilities for improvement with high end-use application in the fashion industry, since it is degradable with high physico-mechanical properties and demonstrate as a viable candidate to reduce non-compostable fabric at landfill sites.


**Figure 2.** Illustration of some new-generation sustainable fiber sources and products. Images reproduced with permission from MycoTech, Pinatex®, Malai.eco and MuSkin (Orange Fiber S.R.L. 2015; Malai Design & Materials 2017, Hungund and Gupta 2010; SwicoFil 2018).

## Milestones in innovations from nature

While researchers and leather producers are increasingly searching for better ways to go sustainable, different technological approaches have been applied to redefine the manufacture fashion materials from conventional sources of animal hides and synthetic materials of PU and PVC. Over the last, several research studies have been performed towards contributing to achieve

a sustainable and eco-friendly fashion market. **Table 2** and **3** presents some research outputs so far in the field of footwear materials processed using agro-derived fibers from academia to the industrial/commercial sector.

**Table 2**. Some research works leather-like materials from agro-derived fibers.

| Samples | Main source materials | Method of fabrication | Properties | Ref. |
|---|---|---|---|---|
| Bacterial cellulose | Green tea | Multi-layer assembly with support systems | Flexible, light, breathable, opaque | (Nam and Lee 2019a; Lee et al. 2014) |
| Bacterial cellulose | Carbohydrates | Exhaustion process of BC membranes with polymer softeners | Flexible, water repellant, opaque, average mechanical strength | (Fernandes et al. 2019) |
| Biocomposite | Cotton | Blending, molding and high temperature curing | Water resistant, breathable, flexible | (Cao et al. 2014) |

**Table 3**. Summary of commercial stage innovations from natural sources for footwear products.

| Innovative Enterprises | Country | Main source materials | Products | Properties | Technology readiness level | Ref. |
|---|---|---|---|---|---|---|
| Vegea | Italy | Vegetables, Grapes | Footwear, Bags, Furniture, Automotive | Durable, flexible, odorless, smooth, chemical resistant, opaque | Commercial | (Vegea 2019) |
| Pinatex | Philippines Spain | Pineapple leaf fibers | Footwear, Bags, Wallets | Flexible, durable, smooth, odorless, chemical resistant | Commercial | (Pinatex 2017) |
| ScobyTec | Germany | BC from carbohydrates | Footwear, Bags, Textile | Durable, Smooth, Flexible, odorless | Commercial | (Material District 2019) |
| Malai | India | BC from coconut | Footwear, Bags, Wallets | Medium texture, flexible, soft, weather and chemical resistant, light, odorless, durable | Early stage, commercial | (Malai Design & Materials 2017) |
| MycoWorks | USA | Mycelium from mushroom | Footwear, Furniture, Textile | Durable, Smooth, Flexible, odorless | Early stage, Research development | (MycoWorks 2017b) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Amadou Leather | USA | Tree mushroom | Footwear, bags | Smooth, soft, non-reflective, opaque, flexible, light | Commercial | (Amadou Leather 2018) |
| MuSkin | Italy | Phellinus ellipsoideus | Footwear, bags, furniture | Light, weak, flexible, opaque, non-elastic, non-reflective, smooth | Commercial | (Grado Zero Innovations 2017) |
| Apple Girl | Denmark | Apples | Footwear, Textile | Flexible, breathable, soft, weather and chemical resistant, light, odorless, durable | Commercial | (The Apple Girl 2017) |
| Fruitleather Rotterdam | Netherlands | Fruit pulp | Footwear, clothing and bags | Soft, smooth, opaque, flexible, light | Commercial | (Fruitleather Rotterdam 2017) |
| Ecovative Design | USA | Mycelium from mushroom | Footwear, Textile, Packaging | Durable, Smooth, Flexible, odorless, opaque | Commercial | (Ecovative Design 2019a) |

## Challenges and limitations towards industrial scalability

Besides the scope of reducing animal cruelty and the confusion between terminologies associated with synthetic fiber degradation abilities, there exist a few hurdles associated with agro-derived fibers usage in footwear materials to be successful in the delivery on their sustainability promise. This is attributed to the increase potentials of cross-contamination with low amounts of different chemical components during the finishing stages of the leather materials. Innovating around these materials is usually associated with a number of significant challenges that includes; the design of complete bio-based leather materials where all fibers and other components degrade fully and safely, providing details on biodegradable fibers, composting routes in cases where other non-degradable components have been incorporated (Fletcher and Grose 2012). Last but the least, the high cost of production for these agro-derived materials sometimes impact the final price of the finished products. For example, the cost of production of bacterial cellulose is still on the high side with several research works in progress towards reducing cost of production of this fiber. However, the low cost of fabric production is one of the main factors driving the sector with gradual increase in the number of consumers opting for agro-derived fabrics, which are sustainable. Moreover, technological advancements in improving the quality of these leather

materials is prompting consumers to prefer agro fashion also known as vegan fashion with several enterprises presently commercializing products obtained from these sustainable sources at affordable prices compare to conventional leather materials from animal hides and synthetic based leather of PU and PVC (Faheem and Khan 2015).

On the other hand, one of the challenges faced is by smaller business where innovative development is their sole asset with uncertainty of the future, which can depict prohibitive to progress. Such companies generally rely on business collaboration with larger established companies which have more expertise in this area and also depend on social media to promote their products. Consequently, the most suitable route to larger scale production for such innovations is by patenting their idea and then search for a more established larger manufacturer to create a market and establish an operational production process that may be sometimes very challenging and rigorous (Wood 2019). Moreover, at the stage of commercialization by either big or small enterprises, one of the biggest challenges lies to prove to consumers (non-believers) the superiority of the agro-derived products over already existing products in the market that is not cruel and in fact is better for the environment.

**Conclusion and future outlook**

From this short review, it is now clear that unlike the use of animal skin and synthetic-based materials of PU and PVC for the production of leather in the footwear industry, agro-derived fibers possess huge potentials and has demonstrated over recent years to be increasingly used as integral components in the manufacture of fabrics in the fashion industry. Moreover, the increasing stringent environmental concerns, is gradually pushing the fashion market towards sustainable materials with more and more interesting research innovations on eco-friendly materials being developed. The fashion industry is ever changing particularly in the footwear and textile sector, which provides a great research widow for state-of-the-art innovation using agro-derived fibers that are sustainable and possess environmentally friendly features. In addition, the production of footwear products from unexplored fiber sources such as biosynthesis pathways that circumvents the usage of toxic chemicals for fiber extraction, will unfold new avenues of material production.

Product transformation from conventional to new apparel fashion areas will greatly contribute to more income for the people in the agricultural sector involved in manufacturing and processing. At the same time, there seems to be a mega scope as the usage of several agro-derived fibers remain

unexplored. Therefore, designers such as manufacturers, institutions and other research organizations should invest more in end-application of materials derived from natural or agro source that will in tend promote significant awareness and competence with regard to commercialization and usage of agro-based products in our day-to-day lives. However, the footwear industry has historically been swayed by nature, by producing products using animal skin and modification of structural principles instead of applying alternative natural sources. For instance, the present global drive of the fashion market is focused on minimizing waste by using agro-wastes from food industry by-products to produce innovative materials, which is highly relevant and promising. For example, innovative alternative sources, such as bacterial cellulose and mycelium being still in their early stages of development, show potential in terms of footwear performance properties. But the cost of production is still on the high side, limiting industrial scalability. Notwithstanding, research over the years proves these developments can be highly efficient and profitable. Though one must be also mindful of the fact that if any of these alternative innovative natural sources are to reach optimum commercial viability, there must reach a standard platform desired consumer.

Typically, in the fashion industry, material flexibility, durability, comfort and wash ability are all potential key parameters, but it is well known in the footwear industry that several of these properties are mainly incorporated via synthetic chemical finishing. This affects the environment and decreases the sustainability of the new materials. Thus, agro-derived alternatives must be moderated via suitable eco-friendly fabrication pathways to ensure the materials meet the state to be displayed as viable substitutes to already existing animal skin and synthetic (PU and PVC) leather materials. Apparently, there exist dramatic change in consumer preference for vegan or agro-derived in the last twenty years. While it still remains uncertain in the trend for the 21$^{st}$ century, it obviously clear that both the footwear and apparel industries needs to be ready to adapt, since research development, the industrial and business sector in these materials sits on the fence of inconsistency, irregularity and ambiguity. Overall, the material shows great promise in terms of prospective business opportunities and lifestyle in the near future.

**Conflict of interest**

The authors declare no conflict of interest.

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