

# Research & Innovation for Sustainable Products: Polysaccharides for a smart circular economy at zero waste

Pierfrancesco Morganti\*<sup>1</sup>, Gianluca Morganti<sup>2</sup> and Marco Palombo<sup>3</sup>

<sup>1</sup>R&D Unit, Academy of History of Healthcare Art, Rome, Italy; China Medical University, Shenyang, China

<sup>2</sup>ISCD Nanoscience Center, Rome, Italy.

<sup>3</sup>Department of Plastic & Reconstructive Surgery and Burn Center, Sant'Eugenio Hospital, Rome, Italy.

\***Corresponding Author:** Pierfrancesco Morganti, R&D Unit, Academy of History of Healthcare Art, Rome, Italy; China Medical University, Shenyang, China.

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## Abstract

Scientific Research and Innovation (R&I) may be considered respectively "the spoken language and the written language of every culture". The first is necessary to discover new lands, while the second results fundamental to build houses & roads and make food, necessary for a healthy living. At this purpose, the scientific research may be distinguished in 3 different phases: basic and experimental research, applied research and industrial research.

Innovation comes from the basic research, while the applied research represents the bridge between the basic research and the industrial ones.

**Keywords:** Research Innovation; Sustainable Products; Polysaccharides; smart circular economy

## Introduction

Scientific Research and Innovation (R&I) may be considered respectively "the spoken language and the written language of every culture" (1). The first is necessary to discover new lands, while the second results fundamental to build houses & roads and make food, necessary for a healthy living. At this purpose, the scientific research may be distinguished in 3 different phases: basic and experimental research, applied research and industrial research.

Innovation comes from the basic research, while the applied research represents the bridge between the basic research and the industrial ones [1].

However, the basic research results fundamental to design the criteria by which the scientific knowledge develops technical innovations, necessary for a sustainable development. Thus new

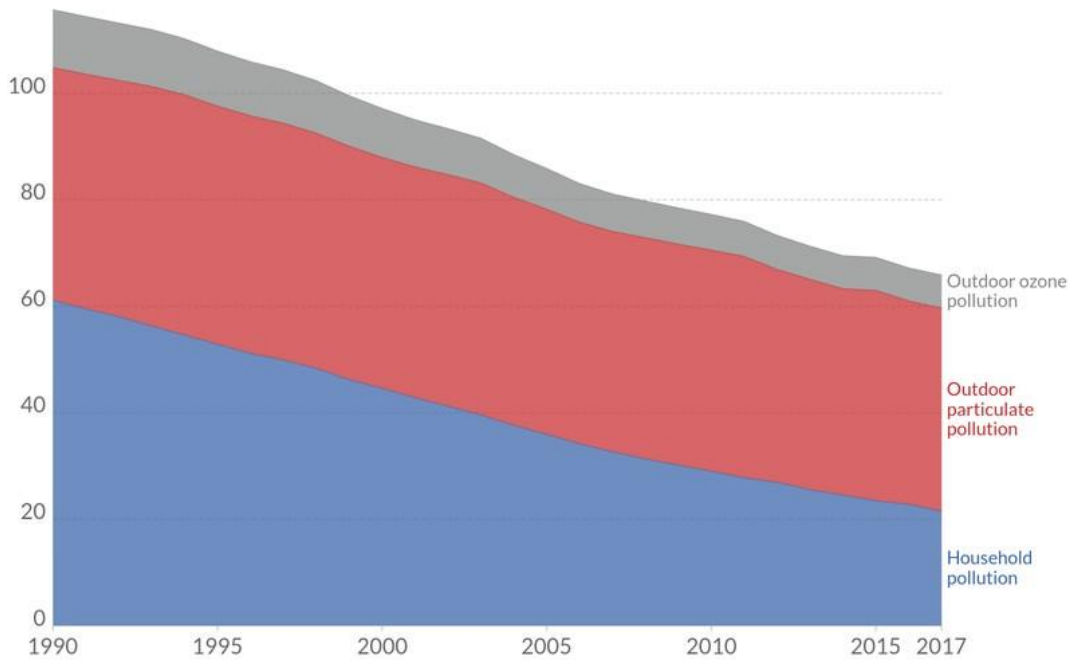
theories have been constructed which, generating new possible scientific applications and technologies, can be engineered by the applied and industrial research, indispensable to realize the designed products. Consequently, the innovative industries may transform their applied researches in technological smart products with a cost-advantage or a significant lead quality over their rivals [1]. However, according to the actual consumer requests, it results fundamental to make products by sustainable raw materials and technologies, possibly at zero waste to preserve human health and the environment [2-4].

## Linear economy versus circular economy plastic-free

It's not to forget that the actual linear economy, based on take, make and produce waste, is provoking increased greenhouse gas emissions (GHG) and climate changing with an estimated global human deaths of around 7 million per year, 3 million of which due to air particulates [5-8] (fig 1).

## Death rates from air pollution, World, 1990 to 2017

Age-standardized death rates from outdoor ozone, particulates, and indoor fuel pollution per 100,000 individuals.



Source: IHME, Global Burden of Disease

**Figure 1:** Worldwide Death rate from outdoor and indoor air particulate (by courtesy of Our World in Data)

Thus the necessity to produce goods by the circular economy, based on reducing, reusing and recycling, possibly at zero pollution level with waste level.

Air pollution, in fact, represents one of the worldwide greatest human

risk, persisting the today particulate pollution level. It, in fact, seems to be the supposed cause which provokes the estimated total loss of 12.8 billion years of life for the global population (fig2)[9].



**Figure 2:** Particulate pollution levels and other injuries contributing to reduce years of life (By courtesy of STATISTA 1[9]).

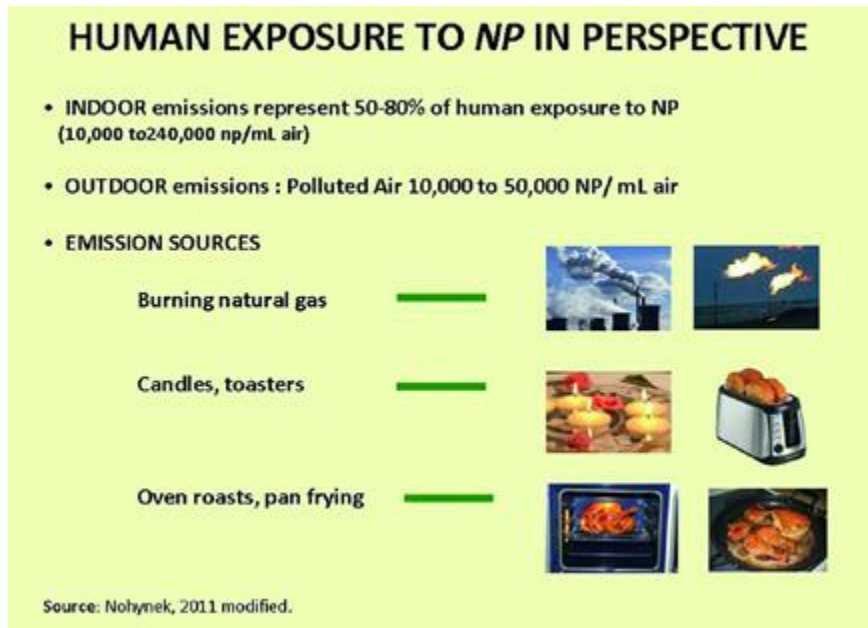


Figure 3: Indoor and Outdoor particulate (by courtesy of Nohynek [14 ])

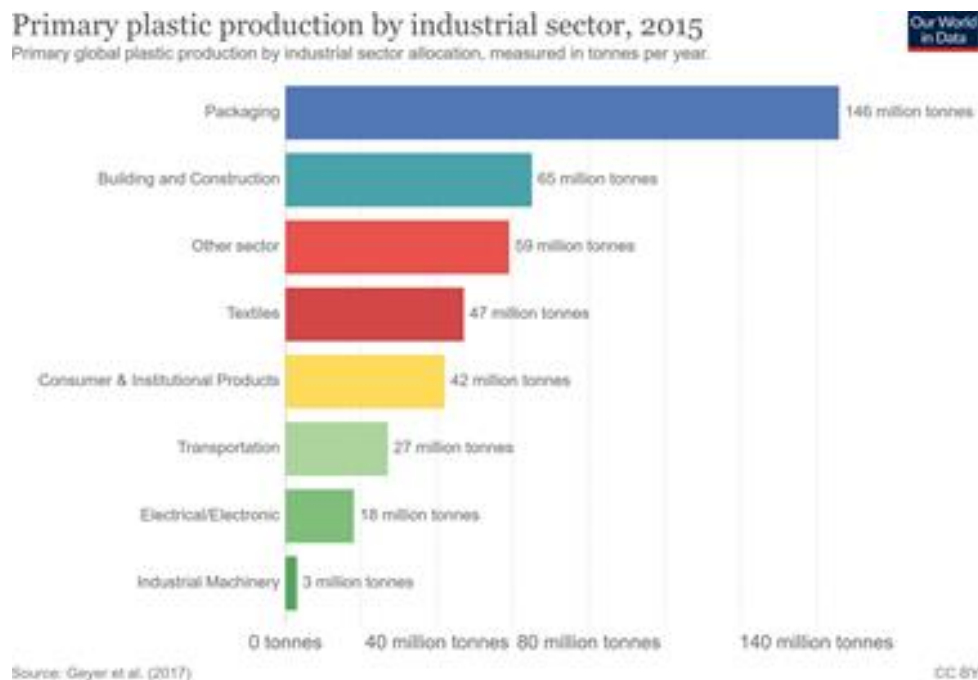


Figure 4: Packaging, Building & Construction, and Textiles are the sector at major consumers of plastic polymers (by the courtesy of Our World in Data)

Air pollution, human health and wellbeing, in fact, are intimately linked to environmental quality and climate changing, impacting on food and water security as well as affecting diseases such as COVID-19 pandemic (10-13). Moreover, it is also to underline that, because of the forced lockdown necessary to eliminate the virus spreading, more than 90% of people are living at home (indoor) where levels of micro-nano-particulate are more higher than in outdoor (fig 3) (14,15).

Therefore through more research studies and investments, it will be possible to realize innovative biodegradable products environmentally-friendly, trying to respect the equilibrium between market structure and innovation. These new smart products would be possibly plastic-free especially in the end-use sectors, such as packaging, building & construction and textiles which utilize around 300 million tons of plastic polymers per year (fig 4) (16,17)



**Figure 5:** Microplastic particles will be more than fishes by 2050 (by the courtesy of Ellen McArthur Foundation [23]).

Another example of unusual pollution is due to the actual great use of non-biodegradable surgical and beauty masks which, filled in the Environment, are increasing the microplastics waste which invade lands and oceans (18-21). It has been estimated, in fact, that going on by the actual "plastic" production and consumption, there will be in oceans more microplastics than fishes by 2050 (fig 5) (22). Therefore, by the actual smart technologies and the circular economy could be possible to make various tissues and biodegradable bioplastic-packagings by the use of polysaccharides, obtained from food and industrial waste. So doing the precious natural raw materials and the Planet's Biodiversity may be safeguarded.

Just to remember in 2016, 242 million tonnes of plastic waste have been generated, representing 12 percent of all solid global waste, which has been estimated to grow by 70 % by 2050, if no action will be taken. Thus industry and consumer. Additionally, in the same year this waste has generated 1.6 billion tons of carbon dioxide, supposed to increase to 2,6 billion tons in 2050. Thus industry and consumer have to change their way of producing and consummating respectively [23,24]. Unfortunately, "cities and countries are rapidly developing without adequate systems" of recycling, thus producing solid waste that affects negatively their citizens [24]. Consequently, the particulate matter pollution generated is responsible for more than 100,000 deaths each year, causing many diseases, including heart attacks, strokes and lung cancer. Moreover, billion of toxic micro/nanoplastics, which invade the oceans, in fact, are entering in the food of fishes and sea-mammals, impacting human food and the health in a manner to be jet better discovered [5-15].

### Research, development & Innovation

Thus the need of more investments and research studies indispensable to utilize the great quantity of waste generated by agro-forestry and food industry for producing innovative goods and tissues (25). At this purpose it is interesting to underline the necessity to support Research and Innovation by new way of inventing, learning, producing, and trading, as reported and shown by the Global Innovation Index [25]. This Index ranks Countries by 80 well defined parameters including political regulatory and business environment, society welfare and scientific and creative outputs, education and R&D expenditure, workers knowledge, infrastructures and ecological sustainability, etc. (fig. 6). By this methodology, it is possible to verify the countries which are investing more in research and development in different sectors, safeguarding wellness, wellbeing, wealth and the environment. Thus the top Countries classified for their leadership Innovation are: Switzerland, Sweden, and Netherland in EU or USA and Canada in North America, Israel in Western Asia or Singapore, South Korea and Hong Kong/China in Asia Pacific. They have been able to conquer and maintain the first positions during the last ten years and the COVID-19 pandemic period also, as reported in figure 7 and 8. [25,26]. However, in 2020 some countries have shown to change its innovation position (fig 8).

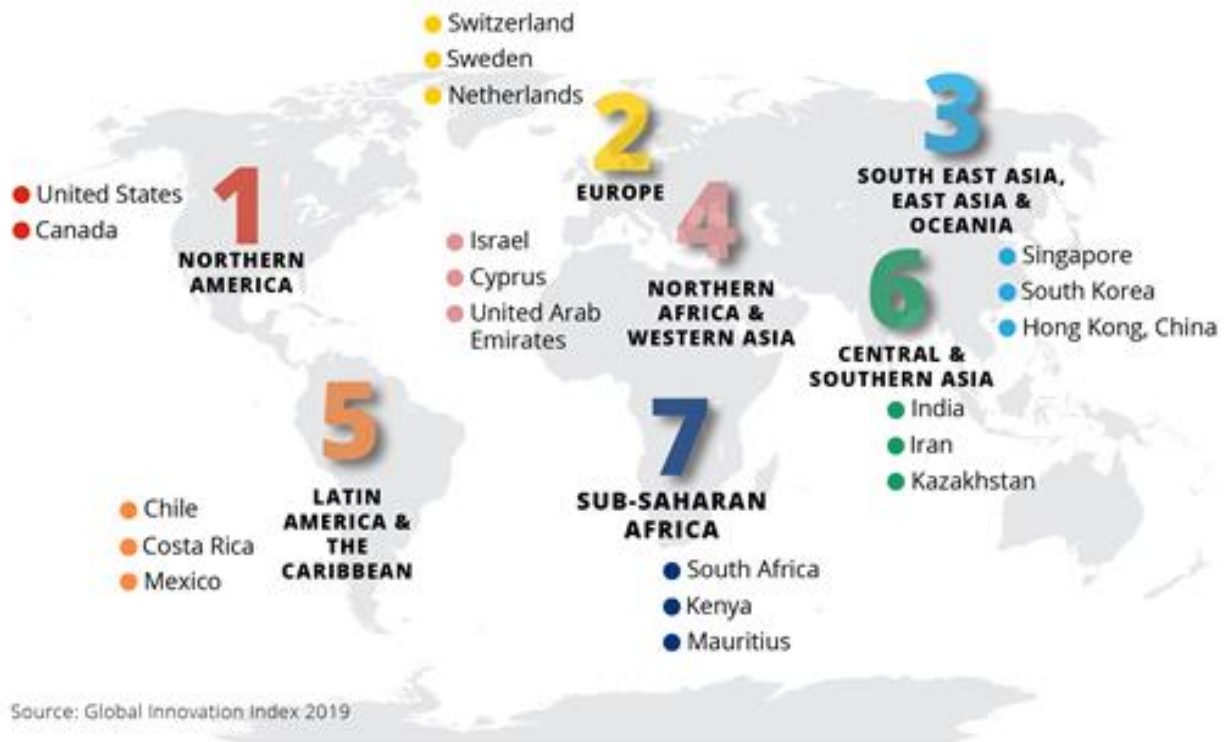


Figure 6: Classification of the Global Innovation Index (by courtesy of Global Foundation Index [25,26])



Figure 7: The worldwide leaders of innovation (by courtesy of Global Innovation Index [25, 26])

## Top innovation economies by region



**Figure 8:** The worldwide Innovation economies by region (by courtesy of Global Innovation Index [25,26]).

In any way, research and innovation are vital to the countries's prosperity, security and wellness. Consequently, innovation should be focused worldwide on the ecological, social and economic transitions accordingly to the European Horizon Program 2021-2027' investments, notably increased during the years becoming from the 1984-1987 period (fig 9) [27]. Innovation, in fact, has a profound impact not only on the global economy, but also on the quality of life, as it appeared evident during the COVID-19 pandemic' crisis which triggered an unprecedented global economic shutdown and a contemporaneous request of wealth with a healthy environment [28]. The greatest innovation happens in fact, during periods of economic crisis like television emerged around the Great Depression, so that innovation has to be considered a key enabler of progress and competitiveness. Thus, innovative research studies may create new categories of solutions by new way of learning, inventing and

producing. According to the World Bank Group President David Malpass, "to overcome the impacts of pandemic and counter the investment headwind, there need to be a major push to improve business environments, increase labor and product market flexibility, and strengthen transparency and governance" [25]. Therefore the innovation, respective of both human health and environment, is the main way to build a sustainable and inclusive future for each country, engineering its growth and economic development by new technologies and fundings. Thus the COVID-19 pandemic, which has triggered an unprecedented global economic shutdown, might catalyze innovation in many sectors such as tourism, education, transportation services, and e-commerce, reorganizing production locally and globally by new smart technologies structured and realized to reduce or reverse long-term climate changing.

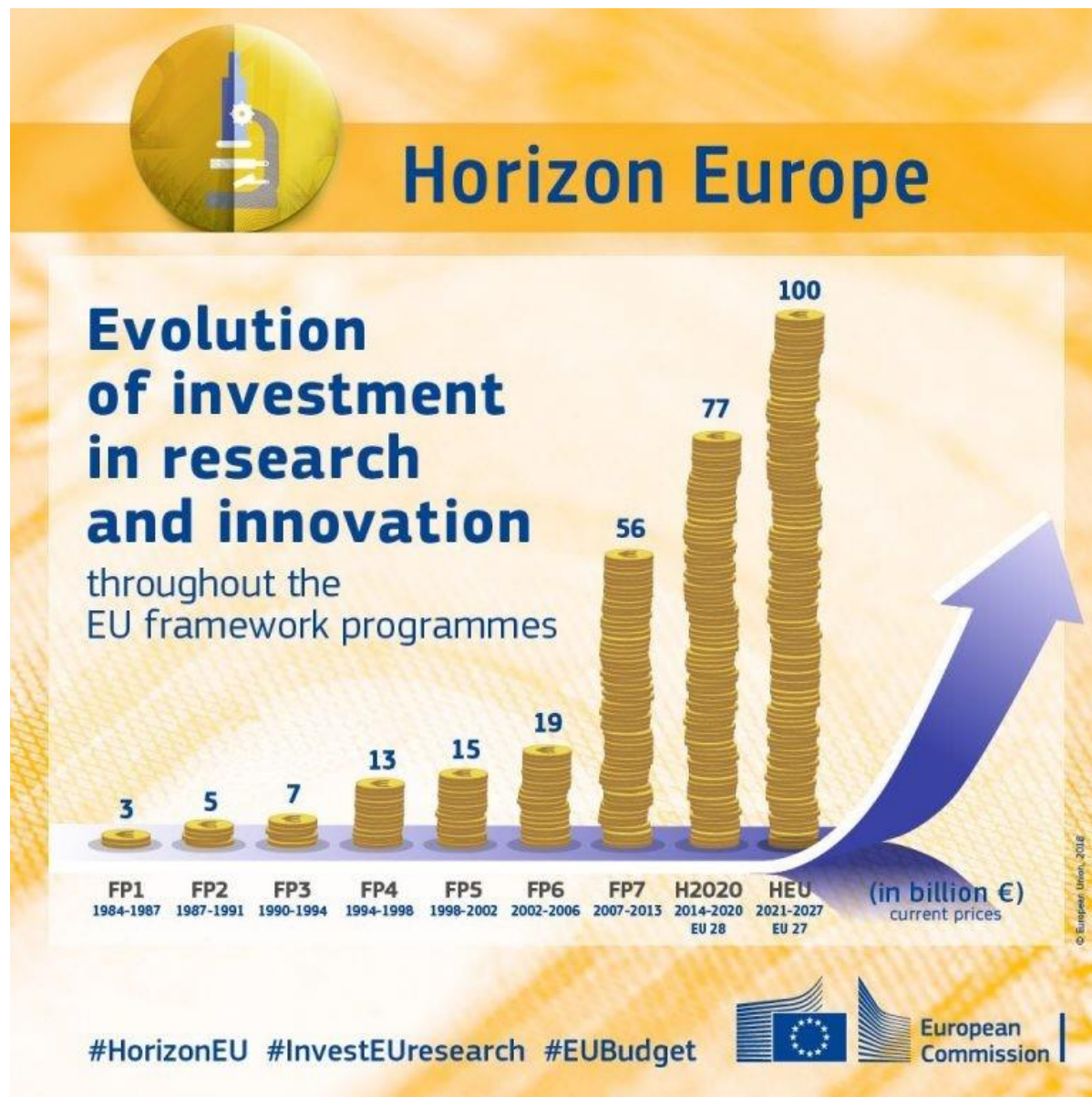


Figure 9: HorizonEU Investments budget from 1984 to 2027(by courtesy of EC [27])

**Food lost, Plastics waste and climate changing.**

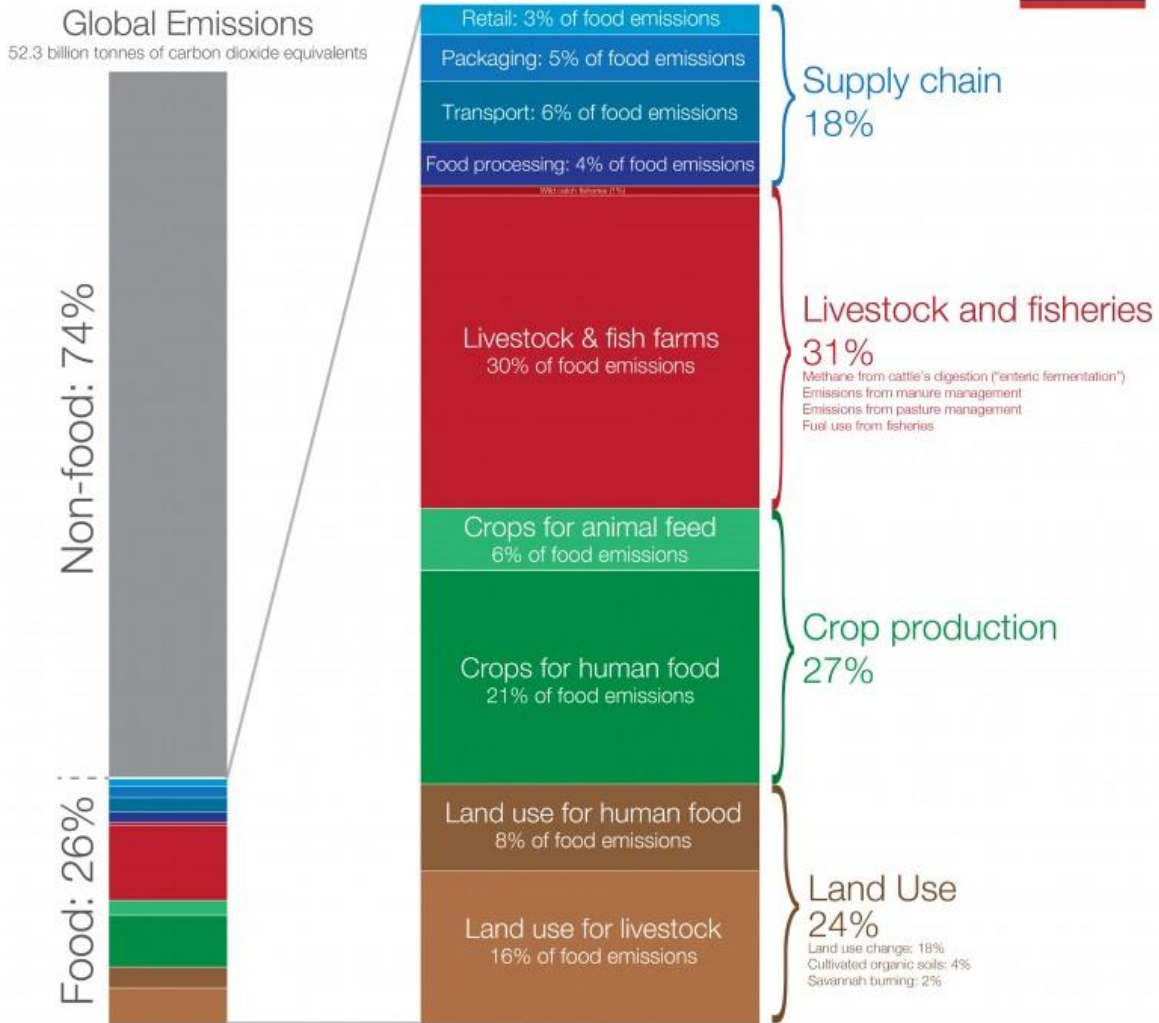
The global food systems is responsible for around 30% of the total GHG emissions due to 1.3 billion tons of food lost every year, while the plastic emissions represents 10/13% of the entire carbon budget (fig 10)[28-30]. On the other hand, it has been estimated that, with the actual production and incineration of plastic material, the annual emission of CO<sub>2</sub> could grow to more than 2.75 billion metric tons by 2050[30]. Global production and use of plastics or synthetic polymers, in fact, has been increased at a compound annual growth rate of 8.3% since the beginning mass production from 1950, surpassing the output of the other man-made materials (fig 11) [31,32]. Consequently, between 1950 and 2017, 9,200 million metric tons (Mt) of virgin plastics were produced, 5,300 of which have been discarded in landfills or the natural environment, recovered into the oceans, as toxic microplastic fibers [33,34]. Moreover as previously

reported, the consumers purchase of more than 80 billion pieces of new clothing each year, translated to USD 1.2 trillion annually, has created other millions of tons (Mt) of textile waste in landfills, with negative implications on both environment and human health[35]. Just to remember it has been estimated that between 1950 and 2016 from the apparel washing 5.6Mt of synthetic microfibers have been filled into the oceans [34,36]. Last but not least, it is to consider that both women and men are using between 9 and 15 personal care products per day, placing daily around 515 individual chemicals on their skin and the environment. Consequently, cosmetics represent another important field contributing to increase the chemicals and plastic packaging' waste, ranging 142 billion units in 2020 [37,38]. For all these reasons as a result of COVID-19 pandemic, the vast majority of consumers worldwide are looking for safety, hygiene and sustainable products plastic-free. They claim to be willing to pay more for reducing the environmental footprint, due also to the packaging materials generating a turnover of

USD 900 billion a year [39,40].However,for customers in EU and Japan,the marine litter is increasingly important,while pollution is more of concern in other Asian and Americas countries.Thus,they rank plastic packaging made by compostable and sustainable materials,accelerating online shopping products,focused even more on health and hygiene (40).Consumers,in fact,are looking for friendly,safe,effective and innovative products,including food,cosmetics and apparel,They feel the responsibility for the world where all of us are living,having an increasing concern for their own wealth,wellness and wellbeing[41,42].It is to recognize,therefore,the impossibility to live a full life without an

healthy body,mind and spirit,strictly connected to the natural environment and climate changing with a reduced GHG emissions.COVID-19 pandemic,therefore,has to be considered a wake-up call to modify our way of living,remembering how the actual global climate changing is damaging human health day by day[43].It,in fact,is projected to have a greater impact in the future,dragging more than 100 million people back to extreme poverty by 2030 with much of this reversal,attributable to negative impacts on health [44].Thus,the growing need for a greater integration among social protection measures,climate change adaptation and disaster risk reduction efforts[45]

## Global greenhouse gas emissions from food production Our World in Data



Data source: Joseph Poore & Thomas Nemecek (2018). Reducing food's environmental impacts through producers and consumers. Published in Science. OurWorldinData.org - Research and data to make progress against the world's largest problems. Licensed under CC-BY by the author Hannah Ritchie.

**Figure 10:** Global greenhouse gas emission from food production (by courtesy of Our in World Data [28])





**Figure 11:** *Plastic waste in the oceans (by courtesy of Jambeck et al [33])*

In conclusion, the increasing waste are producing pollutions and climate changing with an increase of diseases such as the last coronavirus infection. Thus "the necessity to invigorate economies and steer the countries to a prosperous low-carbon future", "helping reinforce economies that COVID-19 pandemic has weakened, and create healthier more equitable communities" [46,47]. This illness, in fact, modifying the likelihood of people habits "has impacted profoundly the consumer lifestyles by a renewed focus on science and nature and sustainability" [46]. Consequently, on the one hand personal health has been prioritized, while the connection between wellbeing/wellness and technology by the digital retail strategy has been accelerated. [48]. Thus the necessity to protect the natural environment that, helping mitigate climate changing by adsorbing CO<sub>2</sub>, could play an important role in preventing the next possible pandemic diseases. Moreover, a major use of natural-derived ingredients, such as polysaccharides, for producing biodegradable goods and tissues may be of great help to reduce production and consumption of petrol-derived plastics and polymers, going versus the requests of scientists and consumers.

### Polysaccharides to produce smart goods and tissues.

The worldwide growth of the population and the constant consumption of natural resources, are exerting a great pressure on the environment, producing waste and GHG emissions. Thus the necessity to use the natural raw materials in the best way, by a circular economy based on sustainable development and recycled waste to preserve a healthy environment for the future generations, according also to the Europe 2020 and Hellen McArthur Foundation' strategies [49-51]. The production of polysaccharides, polypeptides and polymers, including chitin Nanofibrils and Nanolignin are going in this direction, jointing together circular economy (CE), green economy (GE) and bio-economy (BE) based on economic, environmental and social goals, also

if with different geographical distributions: China, in fact, dominates in CE research, EU is prevalently focused on BE, while mostly worldwide researches are based on GE [52-54]. Just to better understand the differences among these research approaches, CE is "focused on industrial urban processes" necessary to decoupling resource use and economic output; BE, represents the integration of science with business and society, being focused "on biological resource-based innovation" with a better land use, while GE "try to envelop an umbrella perspective for a balanced social- environmental development" [52-54]

However, polysaccharides are natural and particularly safe macromolecules which can be extracted at low cost not only from plants, fungi, algae, but also from animals and bacteria. They are polymers consisting of repeating units of sugar monomers, which, extensively used in biomedical and pharmaceutical applications, show a widerange of biological multi-faced properties, including their easy bio/absorbable activity, and antioxidant, immunomodulating, and antibacterial effectiveness [55,56]. The sugar polymers are classified in monosaccharides, disaccharides, oligosaccharides and polysaccharides, and represented by long chains of carbon, hydrogen and oxygen, bound through glycosidic linkages with highly stereo- and regional-controlled arrangements. Among the polysaccharides chitin, lignin and their derived compounds seem to be the more promising natural polymers to be used as healthy and safe macromolecules effective as carrier and active ingredients.

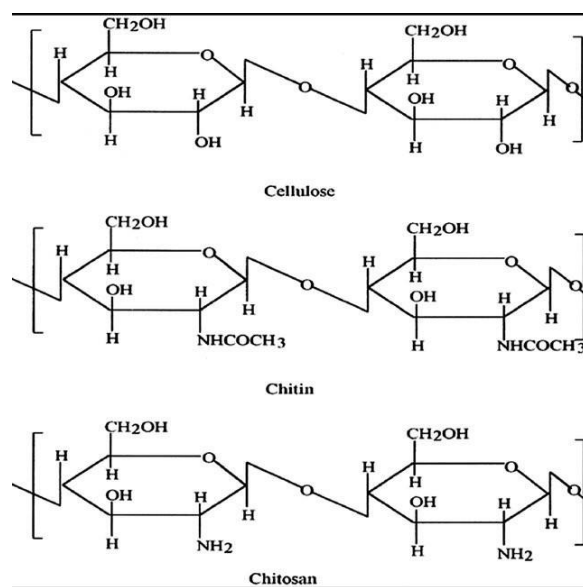
### Chitin and Chitosan

They are natural polysaccharides containing N-acetyl groups and amino groups respectively, characterized for their high molecular weight and high percentage of nitrogen (6.89%), excellent biocompatibility, biodegradability and bio-absorbability with low immunogenicity and toxicity [57,58]. Structurally chitin is similar to the polysaccharide cellulose and, treated by alkali, the polymer lose the

majority of the acetyl glucosamine monomers producing chitosan more rich in glucosamine. Thus, in chitin, the acetylated units prevail being from 40- to 50% and more, depending to the method of industrial production, while chitosan is fully or partially deacetylated from [59%-98%]. However, chitin and chitosan differ not only for their molecular weight and extent of acetylation, but also for the dispersion of the polymerization degree and the various distribution of the acetylated and de-acetylated units, along the polymer chain. All these characteristics affect the chemical and biological properties of these polymers [60].

Chitin is the most abundant second common polysaccharide found in

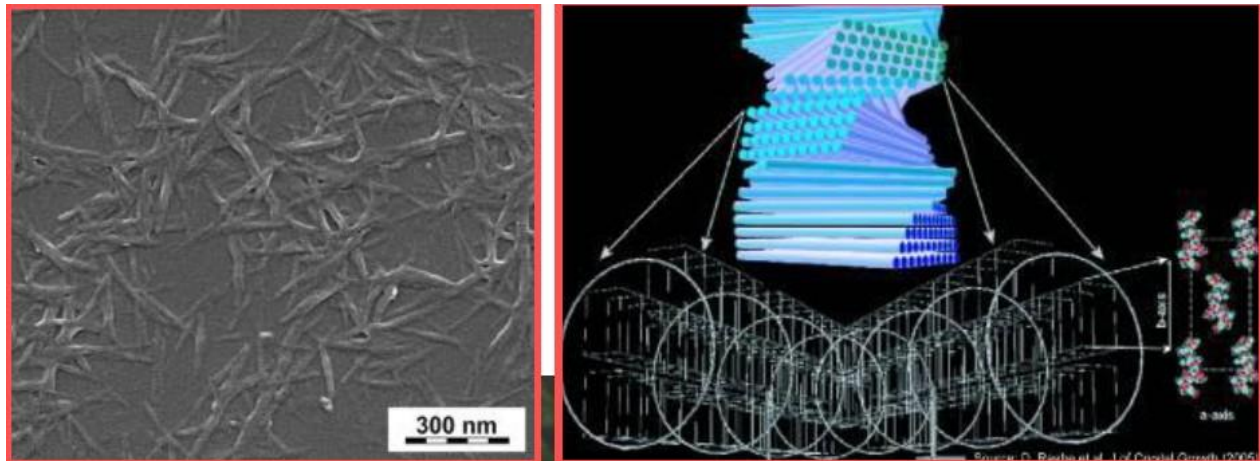
nature after cellulose, being widely distributed in the skeletal material of crustaceans and insects as well as component of cell walls of bacteria and fungi. It differs from cellulose only for the C-2 position of the backbone, where chitin has a N-acetyl group, chitosan an amino group and cellulose an hydroxyl group (fig 12). Depending on the molecular chain orientation chitin is produced in nature in the beta, gamma and in alpha form, as the more frequent. In this last form the polymer appears organized by ordered crystalline microfibril units comprised of 18-25 polymeric chains which create a complex hierarchical architecture [61]. Thus, the acetyl groups of the crystallin alpha-chitin



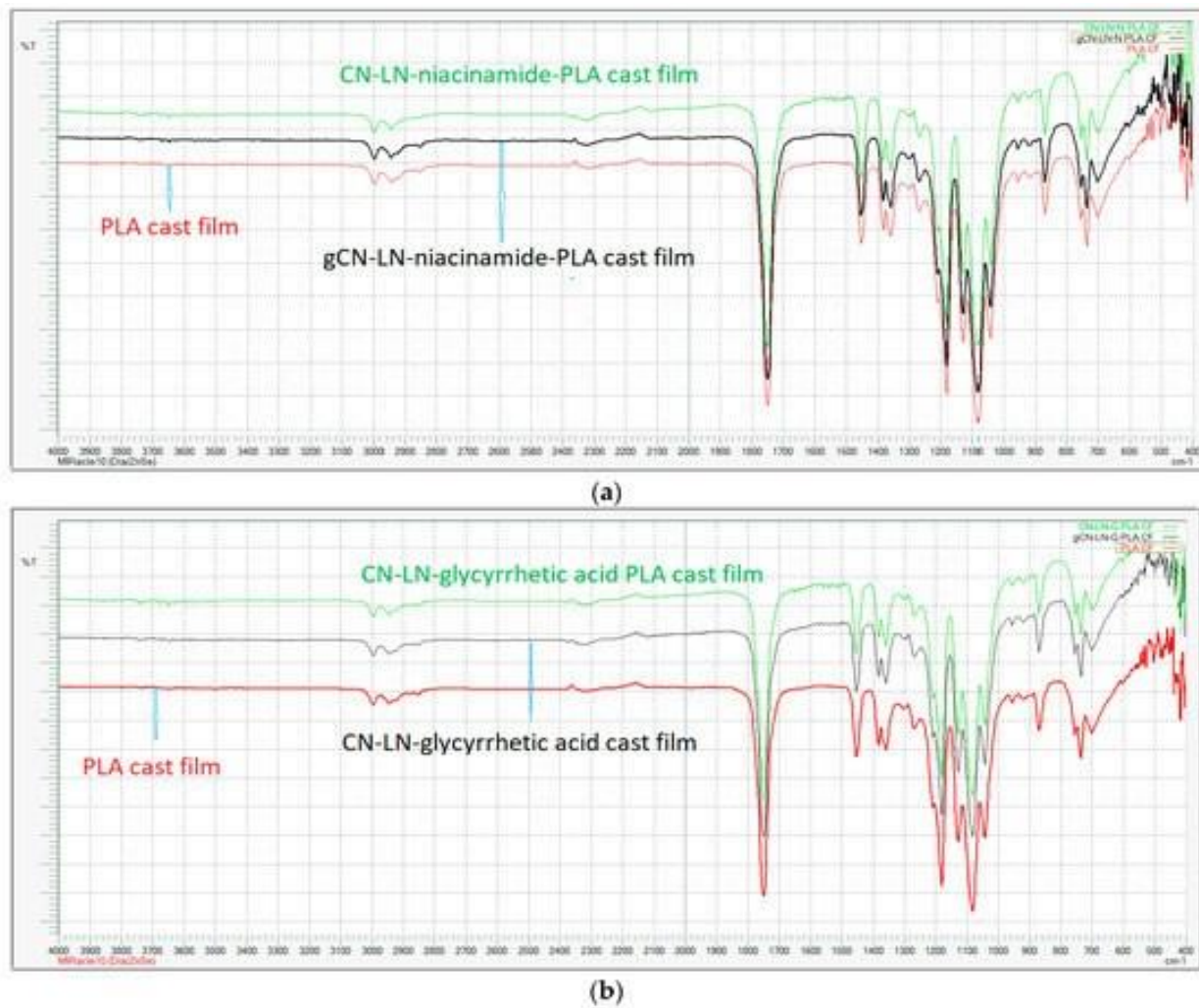
**Figure 12:** Chemical formulation of cellulose compared to Chitin and chitosan

structure represent essential interactive sites, necessary to connect the adjacent chitin chains via hydrogen bonds as well as by other non-bonded interactions. Consequently for example, the bundles of chitin nanofibrils determine the corresponding mechanical properties and flexibility of the final engineered non-woven tissue designed as well as the degree of deacetylation of the polymer leads to the capability of forming more or less hydrogen and covalent bonding at low pH, because of the presence of -OH and -NH<sub>2</sub> free groups [62]. When industrially produced from our group, each chitin Nanofibril (CN) crystal is covered on its surface by around 15.000 positive electrical charges, and shows a mean dimension of 240x7x5 nm (fig 13) with a water uptake capacity of about 400 wt%, at a pH interval between 2 and 4 [63,65]. Thus in water suspension, CN exhibits an interesting capacity to self-assembly natural polymers covered by negative charges as nanolignin (LN), entrapping

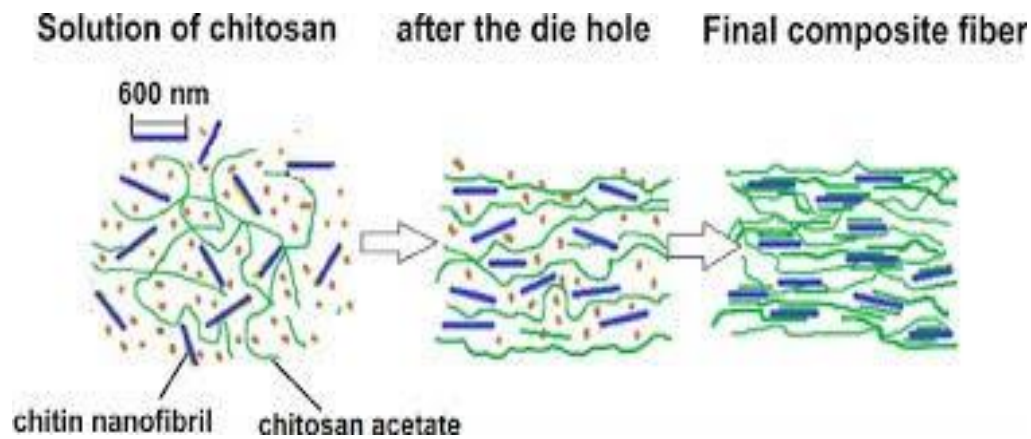
active ingredients as glycyrrhetic acid and niacinamide into films of polylactic acid (PLA) made (fig 14) [66]. Moreover CN, allowing the facility to modify its surface because of the high modulus and strength along the axes of the fiber and the capacity to self-assembly with other natural polymers entrapping different active ingredients, has shown the ability to recreate the natural arrangement of fibrous proteins in living tissues, repairing burns and skin wounds [67,68]. Moreover, CN, contributes to the orientation of the chitosan/chitin nanocomposite and other macromolecules as PLA nanocomposite, increasing its strength and Young modulus of the final designed fibers (fig 15) [69,70]. Probably these various characteristics could be at the base of the effectiveness to repair the skin affected by burns and wounds of tissues made by CN and its complexes [71].



**Figure 13:** Chitin Nanofibrils at Transmission electronic microscopy and its natural hierarchical structure made by antiparallel chains



**Figure 14:** FTIR Spectrum of Chitin Nanofibril-Nanolignin(CN-LG)complex encapsulating respectively niacinamide(a) and Glycyrrhetic acid(b), embedded into a film made by polylactic acid(PLA) and controlled by the Fourier Transform Infrared Spectroscopy(ATR-FTIR) (by the courtesy of Miletic et al [70])



**Figure 15:** Supposed position of chitin Nanofibrils into a chitosan nanocomposite fiber (by the courtesy of Yudin et al [69])

At this purpose it has been shown the facility by which CN-Lignin, bound to nanostructured silver (Ag), make non-woven tissues. Moreover, the tissues have the ability to regulate the cicatrizing phenomena promoting the healing of skin wounds and its repairing activity in a shorter time. Additionally, they don't provoke side effects such as hypertrophic scars and keloids, probably modulating the cytokines activity (67,68). It has been verified in vitro, in fact, that both CN and its complexes with lignin and yaluronic acid stimulate the fibroblasts survival and growth modulating the releasing of both antiinflammatory cytokines and antibacterial defensins [65, 66, 72, 73]. Cosmeceuticals and nanochitin and nanochitosan are suggested as excellent candidates for Biomaterials of pharmaceutical and cosmetic use, including, gel, spray, surgical and beauty masks, and one-day medical dressings [74, 19-21]. Moreover, they are used to develop scaffolds, drug release systems for wound healing, and biomedical applications [61, 65, 66] as well as for cosmeceuticals and active cosmetic tissues [74-76], industrial adsorbents, civil engineering applications [78], water purification [79], protein biosensors [79] and nanofillers in the reinforcement of both natural and synthetic composites to avoid the nano-fibril agglomeration also [61, 81-84].

### Lignin

As previously reported, lignin and its derived compounds complexed with chitin Nanofibrils may be used in the biomedical field to produce films or non-woven tissues to repair burned and wounded skin or to try to slow down the appearance of fine lines and wrinkles [85]. Lignin in nature is a highly branched, three-dimensional polymer built up mainly from three phenyl propane units: p-coumaryl alcohol, conipheryl alcohol and sinapyl alcohol, the mixture of which varies between different

phylogenetic groups of plants, tissues and cell wall layers [86, 87]. These units, named monolignols, consist of phenol and short aliphatic side chains covalently connected by carbon-carbon bonds to form the polymer (fig 16). Thanks to the presence of numerous phenolic groups, lignin possesses interesting antioxidant and UV protective properties useful to make biomaterials for pharmaceutical, cosmetic and diet supplement use [89, 90]. However, it is interesting to underline that chitin-rich peel, present in the beetle shells of certain insects, is impregnated with aromatic polymerized monomers resulting similar to lignin [88]. On the other hand, some fungi and algae produce lignin of identical structure of vascular plants giving them an hard and resistant polymer similar to chitin, synthesizing melanin just as insects and mammals [89, 90].

Thus, chitin and lignin are both natural polymers that can be complexed by the gelation method to obtain nanoparticles able to entrap different active ingredients designed to make innovative biomedical healthy products. Naturally the obtained final nanoparticle properly come not only from the active ingredient selected and entrapped into the complex, but also from its morphology, size and surface charge determined by the purity and concentration of both lignin and chitin, their physicochemical characteristics and the solvent used for its extraction [63, 91]. However, both these polymers may have many potential applications as wound dressings and drug delivery systems depending to the different ways chitin and lignin can be combined with other biomaterials and bio-ingredients to construct innovative composite, biodegradable films and non-woven tissues, as reported from some of our research studies also [20-22, 63-77, 91-93].

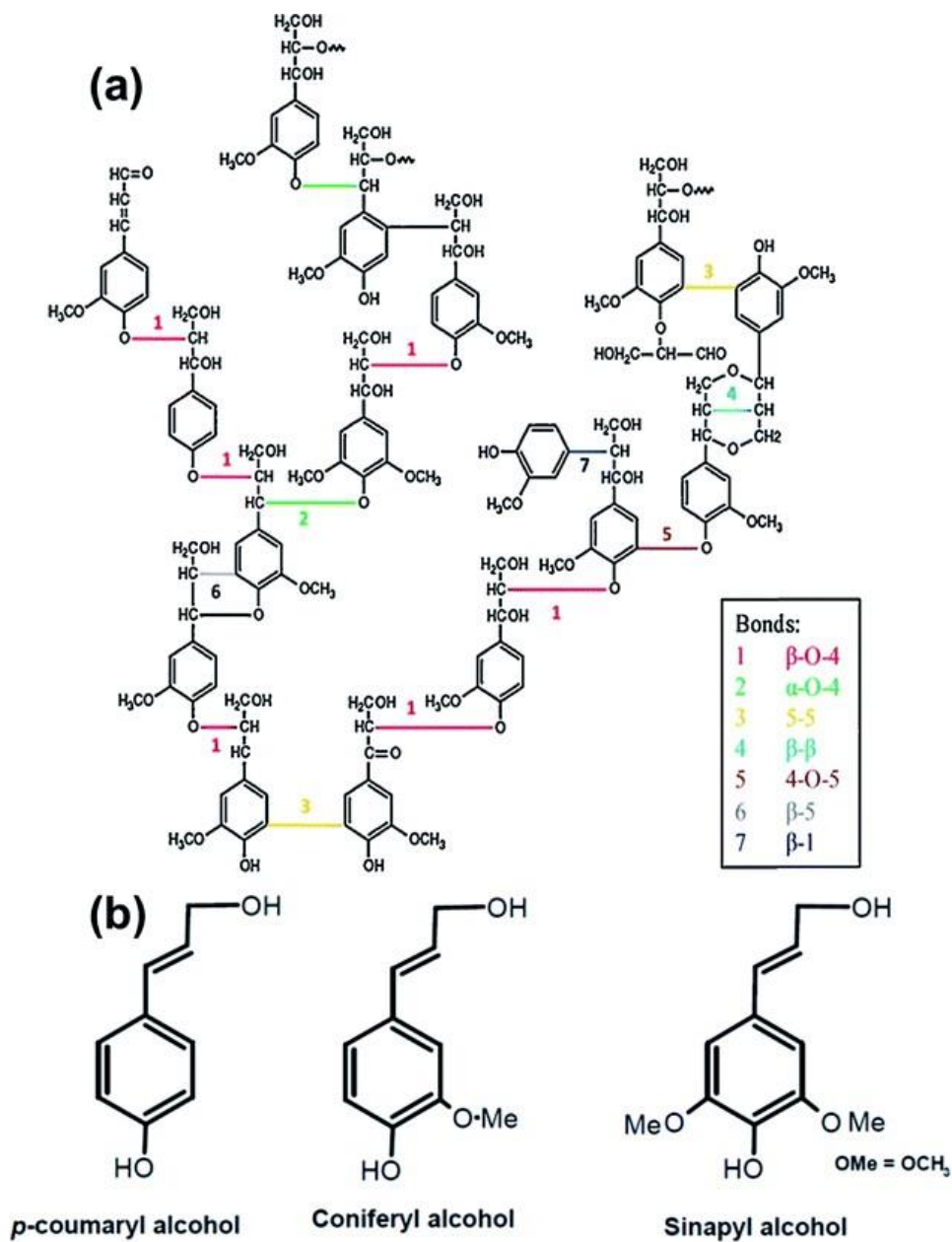


Figure 16: Lignin proposed structure

**Conclusion**

As it has been focused, according to consumers and scientists opinions, plastic production and use, together with food lost, deforestation, overpopulation and great releasing of waste have increased worldwide air and land pollution creating not only worries for global warming and earth disasters but causing also diseases such as COVID-19 pandemic due mostly to human activities and the actual way of producing, consuming and living. Thus, the necessity to change our way of living, recycling not only the textile materials taking the habit to consume less apparel, but becoming also to reduce food lost and waste levels which, accounting for about 8% of the global anthropogenic GHG emissions, represent a significant contribution to climate change (28,94).It is also to underline the further increase of the actual problem of waste which has been forecasted to grow from 260 million tons per year in 2016 to 460 million tons by 2030,if plastic demand will follow

the today trajectory [95].In 2015,in fact, of the 8.3 billion metric tons of plastic produced,6.3 billion will become waste, being actually 9% recycled,12% incinerated and 79%accumulated in the natural environment(lands and oceans) [32].On the other hand, the possible worldwide recycling and reusing of plastic waste at a 50% level, could generate a profit calculated in USD 60 billion by 2030,also if not easy to realize [95,96].However, changing in consumer' behavior during the pandemic has contributed to increase waste and pollution because of the increased shopping on line with more consume of take out food, packed by single-use plastic. But it isn't to forget the majority of GHG emissions(~90%) which results for the manufacture of four industrial commodities such as ammonia, cement, ethylene and steel [97,98].In any way, it results fundamental to change worldwide the way of producing and consuming, investing more in Research & Development to realize sustainable and smartproducts, necessary to maintain and ameliorate

human health and the environment. As previously discussed, climate changing became a great problem that not only harms people worldwide, but also is being cause of further poverty. As reported, in fact from The World Bank Group, it has been estimated that COVID-19 pandemic in 2021 will push in extreme poverty an additional 88 million to 115 million people, affected between 9.1% and 9.4% of the world population in 2020 [99]. On the other hand, this new pandemic has shown that just few months of reduced and altered activity had a beneficial effect on air, water and other aspect of natural world [100,101]. Therefore the climate change- mitigation behavior would be considered worldwide top priority and social norm, which require international collaboration and high education, as happened for the design, study, and production of the COVID-19 vaccine, realized by high level and quick investments [96,100,101]. Thus by a similar global collaboration and investments in R&D among finance, policy, and social science technology-based fields, it will be possible to stop the climate disasters realizing a planet free of pollution and waste human- and environmentally-friendly [94,101]. This is the dream of the worldwide citizens who encompass a wellbeing based not only on food and fitness, but also on overall physical and mental health and appearance. Moreover, after the COVID-19 pandemic, it is increased the consumer' request for sustainable, clean and natural products to ameliorate her/his life-style through wellbeing, viewed through six dimension: better health, better fitness, better nutrition, better appearance, better sleep, and better mindfulness (i.e. a meditation-oriented focused) (102). However, among the worldwide consumers exist differences because, for example, Japanese people prioritize appearance while German emphasize fitness, Brazilian and Americans are more oriented versus mindfulness and Chinese and British people prefer nutrition [102].

Thus, there is the urgent necessity to integrate R&I with the new scientific knowledges and technologies for realizing a sustainable development capable to preserve natural raw materials for the future generations. Moreover, it is our hope that time of the COVID-19 crisis may also be used as an opportunity to invest in policies and institutions to reduce the social, racial and economic inequalities, making the world an equal place for all. In conclusion, the green circular economy seems to represent the goal for creating tools for managing more efficiently land and oceans resources to produce innovative sustainable products at zero waste and pollution. The use of the reported polysaccharides, obtained from food-forestry and industrial waste, seems the best way for achieving the goal to make biodegradable products and packaging materials by sustainable technologies.

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