

Enzymes for consumer products to achieve climate neutrality

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2

3 **Title: Enzymes for consumer products to achieve climate neutrality**

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5 **Running title: enzymes, consumer products and climate change**

6

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45 **LAY SUMMARY** (200 words limit)

46 Accumulated greenhouse gas emissions are expected to increase from 36.2 Giga-tons (Gt) to
47 60 Gt over the next three decades. The global surface temperature has increased by +1.09°C
48 since 2001, and might increase by +2.2°C in 2100, +3.6°C in 2200 and +4.6°C in 2500. These
49 emissions and temperature rises cannot be reduced in their entirety, but they can be lowered
50 by using enzymes. Enzymes are proteins that catalyze biochemical reactions that make life
51 possible since 3.8 billion years ago. Scientists have been able to "domesticate" them in such a
52 way that enzymes, and their engineered variants, are now key players of the circular economy.
53 With a world production of 117 Kilo-tons and a trade of 14.5 Billion-dollars, they have the
54 potential to annually decrease CO₂ emissions by 1 to 2.5 Billion-tons (Bt), the carbon demand
55 to synthesise chemicals by 200 Million tons (Mt), the amount of chemicals by 90 Mt, and the
56 economic losses derived from global warming by 0.5%, while promoting biodiversity and our
57 planet's health. Our success to increase these benefits will depend on better integration of
58 enzymatic solutions in different sectors.

59

60 **ABSTRACT** (250 words limit)

61 Today, the cheosphere's and biosphere's compositions of the planet are changing faster than
62 experienced during the past thousand years. CO₂ emissions from fossil fuel combustion are
63 rising dramatically, including those from processing, manufacturing and consuming everyday
64 products; this rate of greenhouse gas emission (36.2 Giga-tons accumulated in 2022) is raising
65 global temperatures and destabilizing the climate, which is one of the most influential forces
66 on our planet. As our world warms up, our climate will enter a period of constant turbulence,
67 affecting more than 85% of our ecosystems, including the delicate web of life on these systems
68 and impacting socioeconomic networks. How do we deal with the green transition to minimize
69 climate change and its impacts while we are facing these new realities? One of the solutions
70 is to use renewable natural resources. Indeed, nature itself, through the working parts of its
71 living systems, the enzymes, can significantly contribute to achieve climate neutrality and
72 good ecological/biodiversity status. Annually they can help decreasing CO₂ emissions by 1 to
73 2.5 Billion-tons, carbon demand by about 200 Million-tons, and chemical demand by about 90
74 Million-tons. With current climate change goals, we review the consequences of climate
75 change at multiple scales and how enzymes can counteract or mitigate them. We then focus
76 on how they mobilize sustainable and greener innovations in consumer products that have a
77 high contribution to global carbon emissions. Finally, key innovations and challenges to be
78 solved at the enzyme and product levels are discussed.

79

80 **KEYWORDS:** bioeconomy, climate change, consumer products, cosmetics, detergent,
81 enzymes, greenhouse gas emissions, textiles

82

83 **CLIMATE CHANGE: A GLOBAL CHALLENGE**

84 According to the Intergovernmental Panel on Climate Change in its AR6 report from 2021 to
85 2022, greenhouse gas (GHG) reached averages of 410 ppm of carbon dioxide (CO₂), or 0.410
86 g of CO₂/L of air, causing a constant warming uprising during the last four decades [1]. In 1800,
87 the CO₂ level was 285 ppm, a constant value since the year 0 of our era. Increasing GHG emissions
88 are a direct consequence of a continuously growing consumption of fossil fuels that nowadays
89 produce 84.3% of global energy, while only 11.4% comes from renewables [2, 3] (**Figure 1A**).
90 The last time the atmospheric CO₂ concentration reached the current level occurred more than
91 three million years ago [4]. A total of 36.2 Giga-tons (Gt; 1 Gt=10⁹ tons) of CO₂ have been

92 released into the atmosphere, which may increase to 60 Gt by 2050 if current trends continue
93 [5]. If we compare this amount with distances travelled by car (an average European car emits
94 0.175 kgCO₂ equivalent (CO₂e)/km) and the amounts of carbon sequestered by trees (a mature
95 tree sequesters approximately 0.917 kgCO₂e per month), this amount will be equivalent to
96 approx. 342 trillion km (1.5 million times the distance to Mars) and 65 trillion tree-months (21
97 times the number of trees globally) [6]. CO₂ acts as a barrier trapping the sun's heat on Earth.
98 As a consequence, the global surface temperature from 2001 to 2020 increased by +1.09°C
99 (compared to the period from 1850 to 1900) [7]. Scientists from the IPCC foresee at least a
100 50% likelihood that global warming will reach or exceed +1.5°C during the period from 2021
101 to 2040 and an increase of up to 5.5°C over the next century [8,9]. However, other recent
102 projections suggest that mean global warming will achieve +2.2°C above present-day levels by
103 2100, and will continue to rise to +3.6°C in 2200 and +4.6°C in 2500. This warming is also
104 projected to be unequally distributed [10]. As example, over the last 30 years, the temperature
105 increase in Europe was +1.5°C, at a rate of +0.5°C every 10 years, more than double the global
106 average; this being said, GHG emissions in Europe over the same period have been reduced
107 by 31%, and the target is to reduce them to 55% by 2030 [11]. This means that the drastic
108 actions required to fight climate change must go beyond a local scale.

109 CO₂ is not the only molecule directly affecting global warming. Indeed, humans have
110 synthesized more than 140 000 artificial chemicals and mixtures of chemicals, and
111 approximately 220 Billion-tons (Bt) of those are produced and disposed each year, thus
112 contributing also to global warming like CO₂ [12]. The global carbon demand to synthesize
113 those chemicals and derived materials, 450 Million-tons (Mt) per year in 2020 mostly sourced
114 from fossil resources, is expected to increase at an annual rate of 2.7%, reaching 1000 Mt per
115 year by 2050 (**Figure 1B**). This is why massive increase of carbon recycling by 2050 is necessary
116 because *de novo* carbon mining either from fossil or renewables is just not possible in this
117 amount using the technologies available (**Figure 1B**).

118 Different projections and scenarios may have to be reviewed because of the changes that
119 countries are making in response to new realities, particularly to the SARS-CoV-2 pandemic
120 and new political facts. Independently of these revisions, when environment changes, nature
121 has the potential to stabilize itself. However, nature can only respond to slow changes. The
122 only instance that self-equilibration did not occur was approximately 250 million years ago,
123 when the planet warmed up, contributing to mass extinction [13, 14]. To gain some
124 perspective, in the past 2 million years, several temperature changes have occurred on our
125 planet. Before times of industrialization and globalization, a rise of +5°C in global temperature
126 took approximately 5000 years. The increase in GHG emissions and temperature, first
127 acknowledged in 1856, is now happening 20 times faster [15-17]. This rate is too quick to allow
128 nature to stabilize by its own, forcing us to take drastic steps to adapt to the acute extreme
129 heat events that the world is facing [18].

130 Climate change is a global challenge whose effects must be considered beyond 2100 [10].
131 A number of solutions that can help mitigate climate change are currently available, including
132 shift to renewable energy sources, electric. and low-carbon alternatives. These actions also
133 include reduction of food loss, waste generation, deforestation and ecosystems damage, etc.
134 [19]. Such actions, and others to be implemented in the future, are being and will be effective
135 and sustainable in the long term only if socio-economic and policy reforms are considered,
136 and if we all first know the consequences of climate change at multiple levels, from micro- to
137 macro-scale, and also the possible solutions at different levels. Here, we break down some of
138 such consequences and one of the solutions to mitigate or even reverse these deleterious

139 effects. To this end, we need enzymes, which are not only the working parts of living systems,
140 but also constitute one of the cornerstones of a circular (bio)economy.

141

142 **CLIMATE CHANGE: SOCIAL AND ECONOMIC CONSEQUENCES**

143 Climate change is provoking extreme weather phenomena such as large drought periods,
144 more frequent torrential storms, and drastic changes with an overall increase in temperature
145 that will result in the thawing of permafrost and melting of ice at the poles. These factors have
146 a direct threatening effect on biodiversity and human life [20]. The socioeconomic
147 consequences of climate change can also be substantial (**Table 1** [21-50]).

148 From an economic point of view, the total value of equities traded on the world's stock
149 markets is approximately USD 70 trillion per year, and it has been suggested that climate
150 change could cause a potential loss in traded equities of approximately USD 7 trillion per year
151 [41]. The final effect on the global economy will depend on different climate change scenarios
152 and mitigation actions [51]. For instance, agriculture will be the sector most affected by heat
153 stress in the period 2050-2100. This is exemplified by projected total global gross domestic
154 product losses of 2.6-4.0%, agricultural productivity losses of 2-15%, food price increases of
155 1.3-56%, and a food-demand gap of 1.26 Bt [10, 46-48, 52-54].

156 Reducing food and water security and transforming their distribution will affect human
157 health and life expectancy [49, 55]. As an example, a recent study by Carlson *et al.* shows
158 evidence of how climate change can increase cross-species viral transmission risk [56]. Indeed,
159 climate and land-use change will produce novel opportunities for viral transmission among
160 previously geographically isolated wildlife species, facilitating zoonotic spill over, thus
161 increasing the risk of novel epidemic and pandemic outbreaks with already well-known
162 consequences at the social and economic levels.

163 In addition, climate change is expected to affect civil and political rights, including rights to
164 live, access to safe food and water, health, security, shelter, and culture, and contributes to
165 humanitarian crises by creating new problems or exacerbating existing problems for
166 vulnerable populations [57]. Finally, it should be highlighted that all projections
167 unambiguously confirm that the actions we take in the coming years to respond to the climate
168 crisis will determine the future of billions of human lives given that the global effects of climate
169 change are not felt homogeneously across the planet [44]. Indeed, by 2070, approximately 3.5
170 billion people will live in conditions and surroundings with high vulnerability to climate
171 change, and it has been estimated that for every degree of temperature increase, a billion
172 people will be forced to live in uninhabitable places, exacerbating hostilities and giving rise to
173 conflicts [44]. A recent study concluded that the present warming since 1980 elevated conflict
174 risk in Africa by 11% [45].

175

176 **VULNERABILITY OF THE ECOSYSTEMS AND THE ASSOCIATED WEBS OF LIFE**

177 It is important to remark that the vulnerability of humans and ecosystems, including the life
178 forms inhabiting them, are interdependent, and that safeguarding biodiversity and
179 ecosystems is fundamental for climate-resilient development [1]. According to a recent study,
180 more than 85% of the ecosystems will be affected by climate change by 2070-2090, and 16-
181 30% of plant and animal species might go extinct [36-38].

182 It is worrisome that climate change effects on microorganisms are rarely considered,
183 although scientists have warned that there is an urgent need to keep a close eye on this matter
184 [58]. A 16% loss in microbial diversity by 2100 is projected by predictive models if the rate of
185 GHG emissions continues [36, 39]. A redistribution of microbial diversity is also foreseen,

186 causing the composition of bacteria to undergo a strong and generalized global
187 homogenization process across locations [59]. Again, these changes will not occur equally
188 globally or over different taxa [9, 10, 36, 58, 60, 61]. As example, typical desert bacteria,
189 including phylotypes such as *Geodermatophilus* spp., *Mycobacterium* spp., *Venturia* spp., and
190 *Devriesia* spp., and microbial producers of antibiotic resistance genes such as *Streptomyces*
191 spp., will become increasingly common in the future. This will occur because the plasticity of
192 thermal response originates from different strategies of adaptation [62]. Examples include
193 differences in: i) the physiological plasticity, defined as the extent to which an organism can
194 change its physiology in response to environmental cues; ii) the regulation of genes (e.g.,
195 temperature-dependent expression of isoenzymes and/or epigenetic regulation); and (iii) the
196 genetic adaptation that drives the selection of new enzyme variants for which the reaction
197 rate is adapted to changing environmental conditions (e.g. advantageous mutations or
198 acquisition of new genes). The latter mechanism is particularly important in short generation
199 time (and high turn-over) organisms, such as microorganisms, capable of timely adapting to
200 new conditions.

201 The consequences of future microbial redistributions, which may be a direct or indirect
202 consequence of climatic change, are currently not fully understood. As microscopic organisms
203 are necessary for the planet with a crucial role and influence on carbon cycles and the storage
204 of carbon, avoiding its release into the atmosphere, these changes should not be
205 underestimated [63-66]. Indeed, it is assessed that, since the start of the industrial revolution,
206 microorganisms through the enzymes they contain have absorbed almost half of all our CO₂
207 emissions, while also carrying out many essential functions, such as nutrient recycling, crop
208 fertility, detoxification of pollutants, regulation of carbon storage, and even production and
209 absorption of GHG such as methane and nitrogen oxides [67-70]. Therefore, the imbalance in
210 the abundance and diversity of microorganisms expected by 2090 may also contribute to
211 climate change [36,60]. Thus, recent studies have demonstrated that under a +4°C warming
212 scenario, microbial production of CO₂ will rise by 0.05-0.15% as a consequence of global
213 warming and its effect on prokaryotic biomass [40]. At the same time, using a projected
214 warming of +1.9°C by 2100, the carbon sequestration by microbes could decrease by 17 ± 7%
215 [71].

216 All the above, including GHG emissions, hazardous waste disposal, global carbon demand,
217 socioeconomic impacts, and alterations in ecosystems and their delicate web of life (**Table 1**),
218 are some of the issues that need to be addressed regarding climate challenges. It is essential
219 to handle the so-called green transition by developing new technologies capable to help
220 achieving climate neutrality. How do we do this in energy, food, raw materials, consumer
221 products, etc.? These questions need to be solved due to climate change, new realities,
222 including new political facts, and re-politicization of adaptation decision-making [72]. The
223 lessons we have learned from these realities are critical to allow strategic autonomy and
224 building sustainable systems. In this context, it is now accepted that transforming the fossil-
225 powered linear economy towards a circular (bio)economy is critical to our strategy to achieve
226 climate neutrality (**Table 1**). Repowering the industry with enzymes can contribute to improve
227 and accelerate this transformation. This is discussed hereinafter.

228

229 **ENZYMES: KEY PLAYERS TO ACHIEVE CLIMATE NEUTRALITY**

230 Enzymes, as a part of nature, are active proteins that catalyze biochemical reactions. They
231 build and maintain all living organisms, increasing the reaction rates of both syntheses and
232 break down reactions *in vivo*, but also *in vitro* [5, 73]. All living organisms on Earth, including

233 plants, animals, microorganisms, and humans, would never have evolved the way they have
234 without the help of enzymes. Since their initial appearance on Earth 3.8 billion years ago, these
235 catalytic proteins have been allowing life to thrive through adaptations to multiple conditions,
236 including extensive ice ages or global warming, and to new chemicals introduced into the
237 environment, including plastics [74, 75]. This ability to adapt to a multitude of different
238 conditions, i.e. their striking versatility, assigns to them a realistic and outstanding role also in
239 reducing GHG emissions. **Table 2** summarizes the different products that are produced by
240 enzymes. Natural products such as structural protein-based biomaterials or fibres must be
241 extracted and downstream processed before they can be used in different applications.
242 Additionally, a large number of important products for our daily life are manufactured using
243 enzymes *in vitro* including commodity chemicals, bioplastics, and many others.
244

245 How much can enzymes contribute to fight climate change and global warming? Before
246 quantifying their contribution, one should consider the multiple benefits that enzymes can
247 introduce in industrial processes and products: (i) lower energy footprint; (ii) reduction of
248 waste production and chemical consumption; (iii) reduction of environmental impacts across
249 several categories, acidification, eutrophication, photochemical ozone, and energy use; (iv)
250 making process conditions safer; and (v) using renewable feedstocks, to name a few [5, 64-66,
251 77, 78]. As such, the most comprehensive comparative environmental assessments conducted
252 over 15 years have revealed that implementing enzymatic processes in place of conventional
253 chemical ones generally leads to reduced contributions to global warming by saving up to 155
254 kg CO₂ per kg of product, depending on the product [29]. Recent estimations suggest that the
255 full climate change mitigation potential of enzymes may range from between 1 and 2.5 Bt of
256 CO₂ emissions per year by 2030 [27]. This reduction would be equivalent to the annual
257 emissions of about 16-40% of all cars on the road worldwide (estimated to be 1.4 billion).
258 Obviously, enzymes have a solid potential to transform our planet into a global powerhouse
259 to drive the green transition (**Table 1**). In addition, carbon tax implementation (USD 40-80 per
260 tonne CO₂) is expected to force industries not only to reduce their carbon footprint, but also
261 to convert CO₂ into valuable chemicals and materials, which is key to reduce CO₂ emissions
262 into the atmosphere [79]. Here, enzymatic processes may have a key role [5]. Enzymes also
263 contribute to lowering the carbon footprint by supporting the production of about 90 Mt bio-
264 based chemicals, which represents about 0.04% of the total chemical worldwide demand
265 (**Table 1**) [12, 35].

266 It is worth mentioning that not all enzymes contribute equally to the fight against climate
267 change, simply because their different performances and because the products or processes
268 they assist may have a greater or lesser impact in terms of energy, water and chemical
269 consumption and waste generation. For example, one of nature's fastest-working enzymes,
270 carbonic anhydrase, reacts 1 million times per second to convert CO₂ into HCO₃⁻ (bicarbonate).
271 As such, this enzyme together with other CO₂-converting enzymes has greater potential to
272 help fight climate change, contributing to the capture of 14% of the GHG emissions that needs
273 to be reduced by 2050 [80, 81].
274

275 **THE GROWING CONCERN OF CLIMATE CHANGE REQUIRES NEW ENZYMES**

276 It is estimated that our planet is home to 1 trillion (10¹²) microbial species living and operating
277 in a broad range of working conditions, although only approximately 420 000 have been
278 formally described in GenBank. Additionally, the amount of DNA sequences representing
279 different species deposited in databases is huge with the number of bases doubling

280 approximately every 18 months [82, 83]. Every strain, representing each species, is expected
281 to be a wide reservoir of enzymes [84]. As an example, the genome of a single bacterium, such
282 as *Escherichia coli*, contains 4391 predicted genes, among which approximately 607 are
283 enzymes catalysing more than 700 reactions. A single fungal strain contains more than 16 000
284 genes, among which at least 800 are enzymes that support at least 1069 reactions. However,
285 the estimated diversity of some environmental samples reached 100 000 microbial species
286 per gram, which theoretically overestimates the number of enzymes at our disposal [85].
287 Indeed, it is estimated that nearly 10^{10} - 10^{15} proteins exist across all life forms inhabiting our
288 planet, 40% of which may be catalytically active proteins, that is, enzymes [86].

289 This astronomical number is far from the number of enzymes we have been able to
290 observe and to have in our hands. Thus, approximately 270 000 enzymes have been identified
291 that all together support approximately 6500 different reactions; the protein structure of 170
292 000 of them has been characterized [84, 87, 88]. What is significant is that with these enzymes,
293 which represent a tiny fraction of those at our disposal in ecosystems, significant global
294 economic and environmental achievements have been made (**Table 1**). The following data
295 serve as examples: the worldwide enzyme production reached 117 Kilo-tons per year [43];
296 nowadays the trade in enzymes represent 0.037% of total world trade (ca. USD 14.5 billion)
297 with a projected annual growth rate from 2022-2028 up to 6.5%; and enzymes are expected
298 to reduce economic losses derived from global warming by 0.5%, and if enzymes become more
299 important, they should contribute to gain [42, 43]. Access to, or design of a higher number of
300 enzymes will thus allow the industrial reconversion needed to complete the green transition
301 and to achieve climate neutrality.

302

303 **SUSTAINABLE CONSUMER PRODUCTS TO FIGHT CLIMATE CHANGE**

304 The use of enzymes, whether they are new or naturally occurring enzymes, will contribute
305 significantly to the protection of the environment. This occurs during production, use, or
306 disposal through the conservation of resources, reducing global GHG emissions, promoting
307 energy-efficient processes and the use of renewable energy, minimizing the use of toxic
308 agents, reducing waste, and conserving water [5, 89, 90] (**Table 1**). Therefore, enzyme-derived
309 products have the potential to benefit both the environment and our quality of life [91, 92].
310 Together with these benefits and stringent environmental regulations, the main driving force
311 supporting the green trend in industry is related to the increased concern of consumers
312 regarding climate change and the environment and the augmented awareness of the impact
313 consumers can have on their everyday consumption choices. Indeed, according to Silva de
314 Oliveira *et al.*, ca. 90% of consumers will buy a product with an environmental benefit and
315 have a more positive image of a company that supports biotechnology [93]. Furthermore, 50%
316 of consumers are willing to recognize a green premium for a more sustainable greener
317 alternative. This consumer trend is important, as there is strong evidence that consumption
318 habits are interlinked with awareness of climate and environmental change [94]. Thus,
319 changes in consumption behaviour can significantly decrease environmental impacts [95]. For
320 example, negative environmental impacts are expected to decrease if sustainable choices,
321 instead of fashion choices, are prioritized. Indeed, in the 21st century, the fashion industry has
322 been found to be responsible for 10% of GHG emissions [94]. Therefore, constant innovation
323 is needed to pursue a 100% sustainable model of production and consumption that could help
324 to effectively fight climate change while even improving the quality of goods.

325 Below, we review to what extent enzymes can mobilize sustainable and greener
326 innovations in consumer products, to mitigate and even reverse the effect of climate change.

327 In particular, we focus on textiles, detergents, and cosmetics that contribute globally to carbon
328 emissions (**Table 1**), which can be reduced by the use of enzymes.

329

330 **GREENING TEXTILES THROUGH ENZYMES**

331 The contributions of the textile industry to climate change depend mainly on the type of
332 textile. However, one of the main environmental issues in the process chain of textiles is that
333 finished textiles commonly do not meet the desired requirements in the final inspection and
334 return to production to achieve improvements. Such production and correction cycles, which
335 are large chemical and energy-consuming processes, make the textile industry one of the
336 largest contributors to climate change, with up to 10% of GHG emissions occurring worldwide
337 [25]. Each kg of plastic-based fabric emits on average approximately 11.9 kg of CO₂, which
338 accounts for a total of approximately 1291 Mt CO₂ (equivalent to 7.3 trillion km travelled by
339 car), given the worldwide production of 119 Mt textiles [24,25] (**Figure 2A**). Therefore, being
340 more aware of the impact of their purchasing decisions, textile sustainability is becoming an
341 important new driver for industries and consumers [96].

342 To pursue a greener textile industry, different eco-responsible approaches are being
343 investigated and developed [93, 97, 98]. They include: i) the utilization of alternative sources
344 of fibrous raw materials that mitigate the negative impacts of traditional cotton culture, such
345 as bamboo; ii) the utilization of natural dyes and pigments; iii) the use of supercritical CO₂ for
346 reduction and cleaning operations, instead of water; iv) the production of durable and high-
347 quality fabrics; and v) the implementation of heat recovery, so the energy used to warm water
348 (especially in the dyeing and finishing processes) comes from that generated in other steps,
349 such as the stentering frames or the steam boilers, the use of groundwater for the cooling
350 process and returning it with the same quality, to mention a few. These approaches do not
351 consider the application of enzymes so far.

352 Nonetheless, enzymes also have the ability to play a significant role in supporting the
353 conversion of the textile industry into a zero-waste, zero-pollution, fully sustainable market.
354 This potential stems from the fact that enzymes can be applied to all steps of the textile
355 production chain. This may start with the production of biopolymers with the potential to
356 replace common fabrics [99, 100]. Subsequently, the removal of chemicals used in all steps
357 required to achieve the final fabric can be envisaged from the starting polymers, including
358 fibre spinning, weaving and knitting, solvent cleaning, dyeing, washing, finishing, cutting and
359 sewing, in this order [93, 101-105]. This requires highly time- and energy-intensive washing
360 processes that are responsible for the highest amount of GHG emissions, approximately 9.6
361 kg of CO₂ per kg of fabric [24]. Indeed, dyeing of the textile materials requires a significant
362 amount of water, and prior to the dyeing procedure, the removal of sizing products, such as
363 silicones, paraffins, mineral oils, and waxes, is needed. These residual spinning oils added to
364 yarns in order to allow for them to spin, will generate emissions during the drying and fixation
365 steps and can have a negative impact on the subsequent dyeing/finishing processes
366 themselves. Additionally, the processed water is circulated through the system again. The goal
367 of using enzymes is to promote the reduction of the rinsing steps and their duration, optimize
368 the dyeing process, and help discoloration and neutralization of the water resources used. Life
369 cycle assessments demonstrated that enzymes could reduce the overall carbon footprint of
370 fibre spinning, solvent cleaning, dyeing, washing, and finishing of fabrics: 1 g of enzyme can
371 save 0.42-1.0 kg CO₂ per kg of dry weight yarn, which can be translated to a worldwide
372 reduction of approximately 50-119 Mt CO₂, giving the worldwide production of 119 Mt textiles
373 [24, 25, 28, 29] (Filho et al., 2019; UNECE/FAO, 2019) (**Figure 2A**).

374 For this reduction to affect the whole process, the impact associated with the enzyme
375 production must be low. Here, the question which environmental impacts are associated to
376 the enzyme production arises. The carbon footprint of the enzyme production can vary
377 greatly, even for the same enzyme depending on the raw materials, the production method
378 and the transportation. For the most advantageous method, a value as low as 8.9 grams CO₂
379 eq. per gram of enzyme from cradle-to-gate was found in recent life cycle assessments [106]
380 (**Table 3**). These values clearly demonstrate the competitive advantages that enzymes bring
381 to textile bio-processing, and that the contribution of the enzyme production to the entire
382 carbon footprint of a textile bio-process is significantly low.

383 Enzymes will be also essential to avoid the accumulation of recalcitrant garments in
384 landfills. In this context, enzymes can be applied in the biodegradation of the current textile
385 materials in such a way that they can even be reused to produce new recycled textiles.
386 Tackling this issue can prevent our planet from accumulating 3400 Mt of waste by 2030 [107-
387 109]. Note that each second, a truckload of clothes is thrown away or incinerated. Adding
388 enzymes to the recycling process can result in substantial savings of 5.5 kg of CO₂ per kg of
389 textile material compared to chemical processes [30]. If all textiles (119 Mt) were recycled
390 with enzymes, then an overall reduction of approximately 655 Mt CO₂ (equivalent to 3.7
391 trillion km travelled by car) could be achieved.

392 Whether sustainable clothing might be a marketable product rather than a real
393 commitment to reduce environmental impact and climate change, will depend on our ability
394 to offer new enzymes to transform procedures, since a very large amount of textile products
395 is being generated. Such newly-developed enzymes may be directed at least in two key steps
396 required to achieve the fabric on rolls. The first step consists of removing residual spinning oils
397 / sizing products that, if not eliminated, will otherwise generate emissions during the drying
398 and fixation steps. The second step consists in the dyeing process of the textile materials, that
399 needs a lot of water, that further needs to be discolored and circulated in the system again.
400 Currently, these additives/preparation materials and residual dyes are removed by a
401 water/surfactant process and reducing the rinsing steps/duration is the expected goal when
402 adding enzymes into the cleaning processes, and enzymes are needed to support water-
403 based, low temperature, fewer water discharge, and fewer energy consumption processes.

404

405 **GREENING DETERGENTS THROUGH ENZYMES**

406 According to IndexBox estimates, by end 2020, approx. 26 Mt washing laundry detergents
407 were consumed [34]. It is difficult to find reasonable and valid (public) numbers for potential
408 CO₂ annual emissions of washing industry, because the high intra-country variability (average
409 factor of 6.5) in the average GHG emissions related to the laundry washing process [110].
410 However, estimates for more than 840 million domestic washing machines in 2016 suggested
411 more than 62 Mt CO₂, equivalent to 350 billion km travelled by car (**Figure 2B**) [23]. For
412 countries with a mainly fossil-based electricity system, the dominant source of variability in
413 GHG emissions results from consumer choices in the use of washing machines; in this context,
414 predictive models foresee a potential reduction of 39 Mt of CO₂ worldwide per year if water
415 and energy-efficient washing machines are employed [23]. For countries with a relatively low-
416 carbon electricity mix, variability in emissions is mainly determined by laundry product-related
417 parameters. It is at this latter point that enzymes play a major role, being one of the standard
418 and commercially available key ingredients (added in amounts of 0.3-3%) in laundry detergent
419 formulations since decades (early 1970s) to make the washing cycle effective and more
420 sustainable [110]. In this case, we are talking about enzymes that efficiently break down

421 different types of stains to enable the surfactants to better capture and keep these materials
422 in the wash water. Adding these enzymes allows rebalancing the levels of surfactants and
423 washing temperature, which in turn can contribute to lowering CO₂ emissions without
424 compromising washing performance. Indeed, the potential lowering of the energy savings by
425 facilitating reduced wash temperatures and the impact of the use phase of a detergent
426 product, accounting for about 60% of CO₂ emissions, are among the major roles of enzymes
427 in detergent products. As example, the average GHG emissions related to enzymatic-laundry
428 washing processes were estimated to be 500 g CO₂ per wash cycle at 60°C, which can be
429 reduced to 330 g CO₂ per wash cycle when the water temperature is lowered to 30°C, which
430 means a drop of 35% [110].

431 The following three data from the “I Prefer 30°” campaign [31] confirm these arguments.
432 First, the European average wash temperature in 2020 was 42.4°C. Second, 90% of the energy
433 the washing machine uses goes towards heating the water. Third, data collected through the
434 “I Prefer 30°” campaign, which promotes washing at 30°C, estimated a saving of 1307.9
435 GWh/year of current total laundry energy in the five campaign countries, based on a 3°C
436 reduction of the average wash temperature. If a 3°C reduction was to be achieved across the
437 23 European countries, the reduction would be approximately 12% of 22.1 TWh/yr (2.49
438 TWh/yr, equivalent to about 1.4 Mt/year CO₂, and to about 122 000 cars not driven) [111];
439 this reduction can be 18% if the temperature is reduced by 5°C (instead of 3°C). In the USA,
440 this reduction could achieve 2.3 Mt/year CO₂, equivalent to 200 000 cars not driven [32].

441 Implementing better performing enzymes may significantly reduce the carbon footprint of
442 the washing laundry sector further. These enzymes should have strong resistance to laundry
443 ingredients (anionic and nonionic surfactants, chelators, bleach or oxidizing agents) and be
444 efficient enough to eliminate stubborn stains at low temperatures without the extensive use
445 of chemical additives; this is essential to decrease the percentage of chemical surfactants in
446 the detergent formulations and to achieve washing programs with as low emissions as
447 possible. Additionally, enzymes have to be stable at different temperatures to increase market
448 opportunities, as for example in emerging markets, where enzymes and enzyme containing
449 products can be exposed to higher temperatures, especially during transport. In theory, the
450 optimal enzyme has a high robustness against chemical ingredients, is inexpensively
451 producible, and has especially high washing performance at low wash temperatures. Hence,
452 there is plenty of potential of such enzymes for laundry detergents to help achieving climate
453 neutrality.

454

455 **GREENING COSMETICS THROUGH ENZYMES**

456 The cosmetics market is experiencing a fast boost worldwide, with an annual growth of 5.8%.
457 This increase might be attributed to the fact that 34% of males showed more interest in
458 cosmetics products and purchased these goods at higher rates than ever before in early 2020,
459 while the current interest from women was maintained [112, 113]. In particular, the skin care
460 industry is projected to increase by 24.3% from now to 2025 [114]. While cosmetic products
461 are produced and used (approximately 5 g person/year) in less volume than detergents or
462 textiles, their consumption also leads to a major environmental impact, reflected by the fact
463 that more than 120 billion units of cosmetic products are released worldwide into the
464 environment each year [115]. In this scenario, cosmetic companies are emphasizing the fight
465 against climate change, as revealed by an analysis of sustainability report topics, therefore
466 applying strategies to reduce their impact on the environment [116]. Accordingly, there is a
467 growing attention directed to obtaining new sustainable bioingredients produced with the use

468 of enzymatic technologies [117]. Indeed, in the manufacturing of personal care or cosmetic
469 items, the production and extraction of active ingredients are the major sources of
470 environmental impact, accounting for approximately 20% of the total impacts of cosmetic
471 items. Recent estimates foresee from 0.78 to 2.33 kg CO₂ per 1 kg of final cosmetic product,
472 which considering a global production of approximately 10 000 tons of cosmetics and personal
473 care products, will account for a total of 8-23 Mt CO₂ (equivalent to 45-113 billion km travelled
474 by car) (**Figure 2C**) [26]. These emissions are expected to be lowered by 23% if eco-ingredients
475 are produced with enzymes [26]. As for the textile and detergent sectors, implementing novel
476 and better performing enzymes, capable of supporting water-based and fewer energy
477 consumption processes with which to produce cosmetic ingredients, may significantly reduce
478 this carbon footprint while offering innovative consumer products.

479

480 **SYNERGY TO BETTER BIOPROSPECT AND DESIGN NOVEL ENZYMES**

481 As discussed before, the growing concern on climate change and the request for greener
482 consumer products require the search for or design of new enzymes capable of maintaining
483 high catalytic performance during a number of uses and catalytic cycles in an enzyme's
484 lifetime, and whose production cost and carbon footprint is as low as possible [106, 118]. This
485 last issue is currently feasible through platforms capable of managing and testing the high-
486 throughput expression of more than 1500 enzymes per experiment [119]. The option to find
487 such new enzymes, although being challenging, costly (€30k per enzyme) and time-consuming
488 (15 months per enzyme), is realistic given the recent technological advances. Indeed, the use
489 of bioinformatics, machine-learning, accurate protein structure prediction, and data-driven
490 artificial intelligence techniques, are essential to fully exploit the potential of sequencing data
491 as a source of new enzymes (**Figure 3**) [120, 124].

492 These developments must go hand in hand with experimental strategies to test
493 computational predictions and platforms that speed up their incorporation in appropriated
494 synthetic biology chassis and their repurposing through novel engineering techniques with
495 ultrahigh-throughput methods [120, 125-129] (**Figure 4**). To highlight, for more than 98% of
496 natural enzymes the average catalytic efficiency (k_{cat}/K_M) value is $\sim 10^5 \text{ M}^{-1} \text{ s}^{-1}$, and it is desired
497 that k_{cat}/K_M values approach the physical limit of diffusion rate ($\geq 10^9 \text{ M}^{-1} \text{ s}^{-1}$), to ensure their
498 industrial transfer [130]. Pending access to such natural enzymes, these levels can be achieved
499 using engineering techniques. Indeed, artificial intelligence (AI) techniques are being used to
500 create completely novel enzymes that open the possibilities to enrich industrial applications
501 because of their increased properties [131, 132]. Thus, the list of potential enzymes, including
502 those, is almost infinite!

503 But for the synergy between these techniques being effective, it is essential to link
504 sequences encoding enzymes with the specifications (for example, enzyme's activity, stability,
505 lifetime) and needs (for example, substrates to transform, working conditions, etc.) of
506 industries [133]. In relation to this, it remains to be clarified whether current machine-
507 learning, AI, and engineering techniques would be effective when applied to new enzymes
508 and to approach future climate concerns, or whether new tools would need to be
509 implemented, such as data-driven predictive tools (**Figure 3**).

510 Clearly, the potential of computing and AI for searching or repurposing enzymes, will
511 depend on available computing capacities. As an example, if one uses a personal computer
512 with a single core at 3.6 GHz, the search of enzymes in sequence databases may take
513 approximately 142 minutes (or 1.86 g CO₂ emission) using Diamond (as the fastest search
514 standard). The same analysis using a computing cluster takes approximately 18 minutes (or

515 0.11 g CO₂ emission) using the minimum configuration with a single node composed of 40
516 cores at 2.5 GHz, from a hypothetical maximum of up to 134 nodes. Finally, if one has access
517 to cloud resources (with up-to-date hardware), the search for a single genome usually takes
518 1-5 minutes (or 0.06 g CO₂ emission) [134]. A search for an enzyme encoded somewhere in
519 the entire DNA from an environmental sample, the metagenome, that is sequenced,
520 assembled, annotated, and classified *de novo* and further subjected to molecular simulations
521 and virtual screening causes estimated carbon footprints of the average computational
522 running times range from 113 to 5477 kgCO₂e [6]. This amount is equivalent to the amount of
523 carbon sequestered by 103-5020 tree-months, or 19-958 km travelled by car. Thus, it is
524 difficult to estimate what the carbon footprint associated with the screening of a single
525 enzyme would be, given that these data refer to the analysis of samples whose enzyme
526 content is *a priori* unknown, but values ranging from 0.008 to 0.38 kgCO₂e per enzyme may
527 be suggested (**Table 3**).

528 Access to advanced supercomputers and AI would not only enable faster searches but also
529 minimize the associated carbon footprint. As an example, it is worth noting that, considering
530 all possible applications, AI, information and communication technology (ICT),
531 supercomputers and quantum computing have the potential to reduce GHG emissions by
532 between 2.6 and 5.3 Gt CO₂, equivalent to 14.8-30.3 trillion km travelled by car [135, 136].
533 However, supercomputers still consume a high amount of energy, especially for cooling: the
534 world's supercomputers have an annual carbon footprint in the broad region of 3 million
535 tonnes. Consequently, supercomputing facilities are urgently needed that do not produce any
536 carbon emissions because they use 100% renewable power.

537

538 **DESIGNING NOVEL BIO-PROCESSES FOR DECARBONIZATION**

539 Many of the above-described products and processes will rely on the implementation of more
540 and better performing enzymes. But there is also a need for enzymes that not only make these
541 products and processes more sustainable and environmentally friendly, but also allow the
542 design of novel pathways for CO₂ fixation and ultimately building up products by using
543 atmospheric CO₂. Therefore, developing bio-based CO₂ capture technology at industrial scale
544 will be a very urgent task to decarbonize their production processes [137]. Currently, seven
545 different pathways involved in CO₂ fixation are known and they can be exploited for enzyme-
546 driven decarbonization. The best-studied pathway is the Calvin-Benson-Bassham cycle with
547 ribulose-1,5-bisphosphate carboxylase/oxygenase (RubisCO) as the main CO₂-fixing enzyme
548 [138]. It is used by green plants, algae, cyanobacteria and many other microorganisms. Yet
549 another pathway is the Wood-Ljungdahl pathway. It is well conserved within the acetogenic
550 bacteria and the methanogenic archaea and is often associated with extreme habitats [139].
551 A key enzyme here is hydrogen-dependent CO₂ reductase (HDCR), the only known biocatalyst
552 that can reduce CO₂ to formate using only H₂ as electron donor. As the reaction is fully
553 reversible, HDCR can be used for H₂ production as well as carbon capture and production of
554 formate as a starting material for a variety of high value products [140]. In addition, nature
555 has evolved efficient few other pathways to fix CO₂ from the atmosphere among them the 3-
556 hydroxypropionate bicycle, the 3-hydroxypropionate/4-hydroxybutyrate cycle,
557 dicarboxylate/4-hydroxybutyrate cycle (DC/HB cycle), and the reverse tricarbonyl acid cycle
558 [141, 142]. Altogether, these pathways and their respective enzymes will be important for the
559 built up of enzyme-driven CO₂ fixing biotechnological processes.

560

561

562 **POSITIVE IMPACT OF ENZYMES ON BIODIVERSITY AND PLANET’S HEALTH**

563 The benefits that enzymes bring in terms of reducing GHG emissions and supporting the bio-
564 processes for decarbonization and recycling carbon from renewables (**Table 1**) have a direct
565 influence on controlling or minimizing climate change and its effects. However, enzymes can
566 also help to reduce the need and consumption of chemicals (**Table 1**), and to establish
567 recycling and biodegradation processes that help to reduce pollution and remediate
568 contaminated sites. This is an important issue as environmental pollution resulting from
569 human activity is detrimental to ecosystems at different levels, such as biodiversity level
570 which, as mentioned above, is crucial to maintain the planet’s health status [36]. Note that
571 recent estimates of bacterial and archaeal diversity suggested the existence of at least 2.2-4.3
572 million prokaryotic operational taxonomic units, that have inhabited on Earth over 3.8 billion
573 years ago, and the diversity and distribution of up to 60% of the global ocean microbiome and
574 85% of terrestrial ecosystems are associated with temperature and contamination [36, 143,
575 144]. They co-exist with higher complex forms that includes plants, animals, fungi, and single-
576 celled organisms with true nuclei (that is, all “eukaryotes”), of which about 1.8 million species
577 are being described to date through the Earth Biogenome Project [145]. The grand aim is to
578 minimize the influence on, or even rehabilitate or restore, the biodiversity of our ecosystems.
579 Enzymes, as part of the nature-based solutions and circular bio-based systems, have the
580 potential to substantially contribute to avoid the release of chemicals to, and remove
581 pollutants from, environmental sites to improve the biodiversity status, thus extending the
582 Natura 2000 network, that marked a significant step forward in environmental management
583 [146]. Access to new enzymes that are not only capable of producing biobased chemicals but
584 also help degrade pollutants in our ecosystems is critical to maintaining biodiversity and the
585 health of our planet [147].

586

587 **CONCLUSIONS**

588 Climate change is here to stay unless humankind manages to knock it off. The only feasible
589 approach encompasses the development of new methods, techniques and processes, mainly
590 aiming at reducing GHG emissions. This is not an easy path, it won’t be all fixed by tomorrow,
591 but it is in our hands to gradually reduce the damage to our environment, which also means
592 to ourselves and all living forms. It is important to remark that signs of the effectiveness of the
593 measures tackled are already beginning to be visible. For instance, in the EU Member States
594 and the UK, fossil emissions in 2019 decreased by nearly 3.8% [148]. This tendency needs to
595 be extended to the whole planet and maintained or, even better, accentuated. However,
596 monitoring this trend will be challenging in the following years because of the disturbances
597 produced by the irruption of the worldwide SARS-CoV-2 pandemic, and the new realities and
598 political facts we are facing [72]. The actions to fight climate change need to be engaged at
599 local and global levels, and at personal, industrial and government levels. There is evidence
600 that eco-consciousness is increasing across all regions and that at least 170 countries and
601 many cities are including adaptation in their climate policies and planning processes [1]. Social
602 media, publicizing, or initiatives like the Earth Hour, the International day of Climate Action,
603 or Fridays for Future are also of great importance to create awareness of the consequences
604 of inaction. The IPCC also calls out a warning: the effectiveness of adaptation to reduce climate
605 risk will decrease with increasing warming, so we all need to grow in the same direction, and
606 we need to do it now, so we can make the world green again. We have demonstrated here
607 that, apart from new policies and actions, more prototypes of enzymes are needed to become
608 techno-economic capable of implementing technologies that can contribute to the

609 sustainable development for a circular (bio)economy, mitigate climate change, and contribute
610 to blueprint roadmaps for avoiding the release of chemicals and for rehabilitation or
611 restoration of ecosystems. At this point, with only several thousand commercially available
612 enzymes, the environmental impacts have already been significantly reduced by 1 to 2.5 Bt of
613 CO₂, including those emissions associated with everyday consumer products [5]. It remains to
614 be quantified what benefits we will be able to achieve if we succeed to access and transfer
615 new enzymes, either native, engineered or *de novo* designed, to industry, thereby offering to
616 consumers innovative greener and sustainable products. The problems persist, but the signs
617 are promising.

618

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625

626 **CONFLICT OF INTEREST**

627 None declared.

628

629 **AUTHORS' CONTRIBUTIONS**

630 M.F. and P.M-E. writing-original draft, review and editing and project administration; all other
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632

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969 FIGURE LEGENDS

970 **Figure 1.** Distribution of primary energy supply worldwide (A) and global carbon demand (in Mt carbon,
 971 with indication of percentages depending on the source) to synthesize chemicals and derived materials
 972 (B). Adapted from [2, 3].

973 **Figure 2.** Schematic workflow of the key steps to produce or bioprocess textiles (A), washing laundry
 974 detergents (B), and ingredients to be incorporated into cosmetics (C), and the benefits enzymes could
 975 introduce in terms of the carbon footprint. Data for textiles according to [30]. Data for washing laundry
 976 according to [23, 31, 32]. Data for cosmetics according to [26]. Abbreviation: WW, worldwide; EU+USA,
 977 Europe and USA (as no reliable WW data are available).

978 **Figure 3.** Schematic workflow for the bioprospecting of enzymes for circular (bio)economy and climate
 979 change mitigation. Shown are the steps related to extraction, sequencing, assembling, annotation and
 980 virtual screening of new enzymes from the metagenomes of environmental samples, followed by their
 981 accurate protein structure prediction, high throughput characterization, and iterative improvement by
 982 engineering; finally, validation of computational predictions to design of predictive tools with which to
 983 artificially design *de novo* new enzymes.

984 **Figure 4.** Schematic workflow for the engineering of enzymes for circular (bio)economy and climate
 985 change mitigation. Shown are the steps for iterative improvement of enzyme performances by either
 986 rational design or directed evolution.

987
 988 **Graphical abstract legend.** Repowering industry with naturally occurring or artificially repurposed
 989 enzymes, to boost consumer products innovations and to achieve climate neutrality.
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993 TABLES

994 **Table 1.** Parameters representing the effect and the consequences of climate change and how they
 995 can be minimized with the help of enzymes.

Parameter	Quantification	
	Worldwide value (year in brackets)	Reductions achieved by using enzymes (year in brackets)
GHG (CO ₂) emissions/year	36.2 Gt (accumulated in 2022) ¹ 60 Gt (accumulated by 2050) ¹ 49 700 Mt (only in 2022) ^{2,3} 700 Mt/year (increase rate from 1990-2019) ²	1000-2500 Mt/year (by 2030) ⁴
Global carbon demand for chemicals	450 Mt/year (in 2020) ⁵ 1000 Mt/year (by 2050) ⁵	45 Mt (in 2022) ⁵ 200 Mt/year (by 2050) ⁵
Total amount of chemicals	220 Bt/year ^{6,7}	90 Mt/year ⁸
Ecosystem alterations	85% affected (by 2090) ⁹	Not quantified

Plant, animal species loss	16-30% (by 2070) ¹⁰	Not quantified
Microbial diversity loss	16% (by 2100) ¹¹	Not quantified
Microbial CO ₂ increase	0.05-0.15% (under a +4°C warming scenario) ¹²	Not quantified
Economy loss	7 trillion USD/year ¹³	0.5% reduction/year ¹⁴
People vulnerability	3.5 billion (by 2070) ¹⁵	Not quantified
Conflict risk increase	11% (in 2022) ¹⁶	Not quantified
Food price increase	1.3-56% (by 2050) ¹⁷	Not quantified
Global food demand	60% (by 2050) ¹⁸	Not quantified
Food-demand gap	1260 Mt (by 2050) ¹⁸	Not quantified
Agricultural productivity loss	2-15% (by 2100) ²⁰	Not quantified

996 ¹According to [4, 5, 21].

997 ²According to [22].

998 ³Approximately 62 Mt, 1291 and 8-23 Mt correspond to the washing laundry, textile, and cosmetic sectors, respectively [23-26].

1000 ⁴According to [27]. This includes: i) a Worldwide reduction of 50-119 Mt/year in the textile sector, according to [24, 25, 28-30]; ii) a Worldwide reduction of 1.9-5.3 Mt/year in the cosmetic sector, namely the bioprocessing of ingredients for cosmetics, according to [26]; and iii) a reduction in the EU of 1.4 Mt/year and in the USA of 2.3 Mt CO₂ in the washing laundry sector according to [23, 31, 32].

1004 ⁵According to [2, 3].

1005 ⁶According to [12].

1006 ⁷The production of 1 kg textile requires approximately 3 kg of chemicals, which according to a worldwide production of 119 Mt textiles [24, 25, 33], can be translated into approximately 357 Mt potential chemicals. In the case of the washing laundry sector according to IndexBox estimates, in 2019 approx. 24 Mt of washing laundry detergents were consumed worldwide, and according to an increase of 9.5% in 2020, the total amount by end 2020 reached about 26 Mt [34], which can be potentially flushed into the water system. For cosmetic sector no reliable data are available.

1012 ⁸According to [35].

1013 ⁹According to [36].

1014 ¹⁰According to [37, 38].

1015 ¹¹According to [36, 39].

1016 ¹²According to [40].

1017 ¹³According to [41].

1018 ¹⁴According to [42,43].

1019 ¹⁵According to [44].

1020 ¹⁶According to [45].

1021 ¹⁷According to [46].

1022 ¹⁸According to [47].

1023 ¹⁹According to [48].

1024 ²⁰According to [10, 49, 50].

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1029 **Table 2.** Enzymes allow, both *in vivo* and *in vitro*, the development of unique and innovative functional
 1030 products (including materials) or processes that are key in the circular (bio)economy. Adapted from
 1031 [76].

Sector	Examples	Number of companies	Number of employees	Total sales in billion €
Automotive sector	Car body parts reinforced by natural fibres, car interior lining and seats based on bioplastics, tyres based on dandelion	17	756 000	36
Building industry	Wooden structures, composite materials reinforced by natural fibres, insulation materials, biobased screw anchors, biobased concrete mixtures	317 300	1 900 000	172
Chemical industry	Bioplastics, biobased platform chemicals	2121	434 313	186
Energy	Pellet stoves, biogas, biodiesel fuel, bioethanol, synthetic fuels, algae, kerosene, enzymes for better oil extraction	923	220 157	466
Agriculture & forestry	Precision agriculture, plant and animal breeding, short-rotation forestry, aquaculture	285 000	1 000 000	32
Mechanical engineering	Bioreactors, bioprocessing engineering, agricultural technology and equipment, greenhouse technology, biolubricants	6277	978 000	207
Pharmaceutical industry	Biopharmaceuticals, medicinal plants and herbs	923	135 773	36
Food & beverage industry	Enzymes, fragrances, amino acids, natural food additives, probiotics, food lupin protein	6000	555 000	41.4
Consumer goods	Biobased tensides, bioactive constituents in cosmetics, enzyme-based additives for cleaning agent	-	-	203
Textiles & clothing	Natural raw materials for synthetic fibres, high-tech fibres made of spider web, plant tannins	1300	111 313	11.33

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1034 **Table 3.** Carbon footprint of key tasks associated to the screen and production of enzymes.

Task	Carbon footprint
Bioinformatic and computational screen	113 to 5477 kgCO ₂ e per analysis ¹ 0.008 to 0.38 kgCO ₂ e per enzyme ²
Production	8.9 g CO ₂ e per g enzyme ²

1035 ¹According to [6].

1036 ²Some of the tasks reported by Grealey *et al.*, 2022, include the analysis of up to approx. 15 000 genes
1037 in a computational run; while the equivalence may not be appropriate, the given carbon footprint per
1038 gene (or enzyme) refers to this number [6].

1039 ³According to [106].

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