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Saloua Fertahi, Mohamed Ilsouk, Youssef Zeroual, Abdallah Oukarroum, Abdellatif Barakat

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# 1 **Recent Trends in Organic Coating based on Biopolymers and Biomass for** 2 **Controlled and Slow Release Fertilizers**

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5

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## 15 **Abstract**

16 The growth of the human population is causing an exponential increase in the need for food.  
17 Fertilizers are one of the most important elements to meet this increased demand and to  
18 ensure global food security. Many enhanced efficiency fertilizers, such as controlled-release  
19 fertilizers (CRFs) have been developed. Although these fertilizers offer many advantages over  
20 prior generations, their high cost of production as well as unfavorable effects on the  
21 environment and soil quality have limited their use. To mitigate these issues, CRFs based on  
22 biopolymers (CRF@BB) represent a new generation of fertilizers produced by coating the  
23 granules with biopolymers. In addition to controlling the nutrient release rate, these products  
24 also enhance the soil quality and they reduce the negative effects associated with conventional  
25 fertilizers. This review summarizes the recent advances in biopolymers and derived  
26 biopolymers used in the area of CRF@BB, the coating technologies, and the parameters  
27 governing the release behavior through organic coating materials, as well as the effect of  
28 coated CRFs on the soil and plants growth.

29 **Keywords:** Fertilizer, soil, plant, biopolymer

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## 53           1. Introduction

54   In light of the continuous growth of the earth's population, the number of humans is expected  
55   to increase from 7 billion in 2014 to approximately 9.5 billion by 2050 [1]. Moreover, global  
56   food needs have increased in parallel with the continued exponential growth of the earth's  
57   population. According to the United Nations Food and Agriculture Organization (FAO), food  
58   production needs to increase by 70% to supply the projected 2050 population [2]. On the  
59   other hand, there is less and less arable land due to urbanization, industrialization,  
60   desertification, etc. To respond to the increasing food requirement, farmers are applying  
61   enormous quantities of fertilizers to maximize the agricultural yield. The world consumption  
62   of nitrogen (N), phosphate ( $P_2O_5$ ), and potash ( $K_2O$ ) fertilizers in 2015 was reported to be  
63   110,027,000; 41,151,000; and 32,838,000 tons, respectively, and forecasts for 2020 are  
64   estimated to be 118,136,000; 45,853,000; and 37,042,000 tons, respectively [3]. However,  
65   this strategy suffers from a number of limitations and generates other harmful problems, due  
66   to agricultural practices and technic as well as the quantities sometimes used in excess. Plants  
67   only consume part of nutrients and the rest is lost in the environment due to rain, irrigation,  
68   fixation, volatilization, etc. This causes environmental, economic, and health problems, in  
69   addition to negative effects on the physiology and the growth of plants, as well as nutrition  
70   quality [1,4–8]. Recently, a number of alternative fertilizers were developed based on biochar  
71   [9], using thermochemical processes (pyrolysis, hydrothermal carbonization, etc.) with  
72   digestate [10] and compost [11] obtained after anaerobic and aerobic digestion of biomass,  
73   respectively, and a combination of biochar-digestate. These biofertilizer formulations enrich  
74   the soil, enhance its properties, and make nutrients available for the plant. Biofertilizers based  
75   on microorganisms have also been developed in recent years [12–15]. In general, these  
76   microorganisms are thought to solubilize the otherwise insoluble nutrients, particularly from  
77   mineral rocks, and to maintain the continuum of nutrient flux available to plant roots.  
78   However, mineral fertilizers remain the richest and most effective source of nutrients.  
79   Controlled- and slow-release fertilizers (CRFs/SRFs) are specifically designed fertilizer that  
80   releases active fertilizing nutrients in a controlled delayed manner matched with the  
81   sequential needs of plants for nutrients. Thus, they provide enhanced nutrient use efficiency  
82   and enhanced yields without suffering from nutrient loss [1]. Coating of mineral fertilizers is  
83   one way to produce CRFs/SRFs. Over time, researchers have adopted a variety of coatings.  
84   Sulfur was tried initially as a coating agent [16,17]. It was an attractive candidate for coating,  
85   but its low wettability and adhesion to the coated core, and the need for conditioning materials

86 to reinforce its sealing, add additional expense to the final product. Moreover, any sulfur  
87 remaining in the soil can react with water, thereby acidifying the soil. Subsequent research  
88 efforts have focused on polymeric materials. These materials are not disturbed as readily by  
89 microorganisms like sulfur coatings [1]. However, another problem arose, namely the  
90 majority of polymers need an organic solvent, such as dichloromethane [18], N, N-dimethyl-  
91 formamide (DMF) [19], or chloroform [20], which are harmful to the environment.  
92 Additionally, most of these polymers are not readily biodegradable after total nutrient release;  
93 which then creates a new source of soil pollution as they lead to an undesirable accumulation  
94 of plastic residues up to 50 kg/ha/year [21]. To overcome these economic and environmental  
95 obstacles, the research focus is shifting towards biopolymers. The choice of biopolymers did  
96 not occur by chance; these materials are cheaper than conventional coating materials [22,23];  
97 they are biodegradable, biocompatible, and nontoxic; and they contribute to improvement of  
98 the soil quality [24,25].

99 The aim of the present review is to provide an overview of biopolymers from biomass and  
100 biodegradable synthesized polymers, focusing mainly on their promising properties as an  
101 organic coating of mineral fertilizer for agricultural applications. Firstly, we briefly have  
102 described the characteristics and properties of different biopolymers used for mineral fertilizer  
103 coating. Secondly, we have explored the literature regarding their use as new and smart  
104 biobased coating organic materials for controlled release mineral fertilizers. Thirdly, we have  
105 detailed their advantages and disadvantages and their impact on soil and plant. Fourthly, we  
106 have given an overview of the different coating methods. Finally, we have proposed and  
107 discussed some perspectives and challenges for objective to improve the use of biopolymers  
108 as an organic coating for agronomic applications.

## 109 **2. Background regarding controlled-release fertilizers and slow-release fertilizers** 110 **(CRFs vs. SRFs)**

### 111 **2.1. Definition, legislation, and classification of CRFs vs. SRFs**

112 Release and slow-release have been defined by Trenkel [26] as follows:

- 113 - Release: The transformation of a chemical substance into a plant-available form.
- 114 - Slow-release: The release rate of a nutrient from the fertilizer must be slower than that  
115 from a fertilizer in which the nutrient is readily available for plant uptake.

116 According to Trenkel [26], a fertilizer can be described as slow-release if the nutrient or  
117 nutrients declared as slow-release meet, under defined conditions – including at a temperature  
118 of 25 °C, three criteria in soil:

- 119 - No more than 15% (m/m) released in 24 h.
- 120 - No more than 75% (m/m) released in 28 days;
- 121 - At least 75% (m/m) released at the stated release time.

122 SRFs are fertilizers in a form that release, or convert to a plant-available form, plant nutrients  
123 at a slower rate relative to an appropriate reference soluble product. Regarding CRFs, they are  
124 engineered to provide nutrients over time at a predictable rate under specific conditions.

125 SRFs/CRFs can be broadly classified into three major categories [1,27–30]:

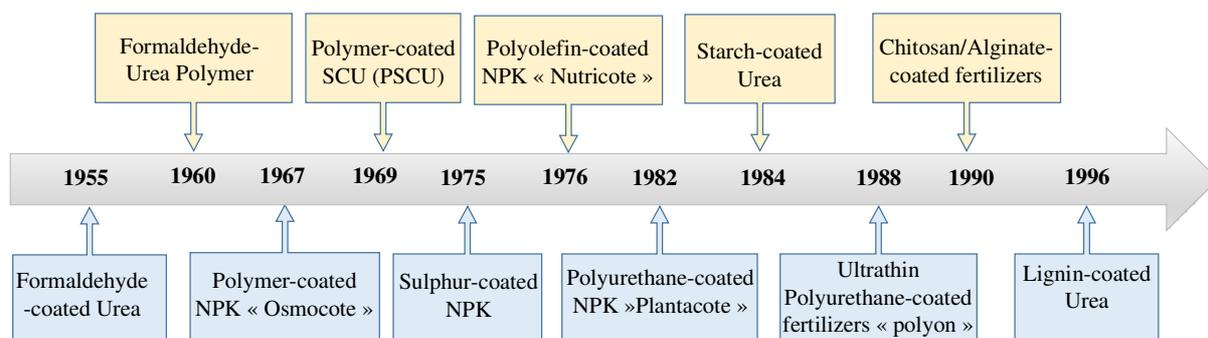
126- **Organic substances:** These are divided into organic-N, low-solubility, and natural  
127 compounds. The former can be divided into biological decomposing compounds that are  
128 usually based on urea-aldehyde condensation products, such as urea-formaldehyde (UF), and  
129 chemically decomposing compounds, such as isobutyledene-diurea (IBDU) or urea  
130 acetaldehyde/cyclo diurea (CDU). The latter includes crop residues, manure, slurry, composts,  
131 sewage sludge, organic-mineral fertilizers (e.g., meat and bone meal, hoof and horn meal,  
132 rapeseed meal, treated leather meal, etc.).

133- **Inorganic low-solubility compounds:** Fertilizers such as metal ammonium phosphates (e.g.,  
134  $MgNH_4PO_4$ ), and partially acidulated phosphate rocks (PAPR).

135- **Water-soluble fertilizers with physical barriers:** These barriers can be generated either by  
136 coating cores or granules with sulfur/polymer materials, or by incorporating nutrients into  
137 matrices that restrict dissolution of the fertilizer. Coated fertilizers can be further divided into  
138 fertilizers coated with organic polymers that are either thermoplastic or a resin, fertilizers  
139 coated with inorganic materials such as sulfur-or mineral-based coatings, and fertilizers  
140 coated with a mixture of sulfur and organic polymers. The matrices can be produced by  
141 hydrophobic materials such as polyolefins, rubber, etc., and gel-forming polymers  
142 (hydrogels). In the past, sulfur was used for coating, but it is rarely used nowadays. Matrices  
143 based on hydrophobic materials or gel-forming polymers are used, but they are less common  
144 compared to coated CRFs. The most used category comprises granule/core fertilizers coated  
145 with organic polymer materials.

## 146 **2.2.History and scientometric analysis of SRFs/CRFs**

147 The first use of the term SRFs dates back to the 1920s, but the concept of SRFs was not  
 148 recognized and was not described until the 1960s by Oertli and Lunt, Woerther, White and  
 149 Hansen [31–35]. Nevertheless, most of the advances occurred in the 1980s and 1990s. Fig. 1  
 150 shows the most well-known applications of slow/controlled-release fertilizers developed over  
 151 the past 60 years. In 1955, the first commercial SRFs product was developed in the USA, and  
 152 it was based on urea and formaldehyde (UF) condensation compounds. This was greatly  
 153 improved by combining it with polymers (urea-formaldehyde-polymer URP) in the early  
 154 1960s. Sulfur-coated urea (SCU) is one of the most common types of coated fertilizers, and it  
 155 is a slow-release fertilizer made by coating urea with sulfur and wax. SCU was developed in  
 156 the USA during the 1960s. However, due to the relatively poor performance of SCU, a  
 157 polymer-coated SCU (PSCU) was introduced to the market. This hybrid coating offered better  
 158 release of nutrient elements, and it was developed in 1969. NPK fertilizers coated with sulfur  
 159 were developed for the first time in Japan in 1975, while polymer-coated NPK was first  
 160 produced commercially in California starting in 1967 under the brand name “Osmocote”. The  
 161 resin used as the coating material is based on a copolymer of dicyclopentadiene and glycerol  
 162 ester. The first controlled nutrient-releasing fertilizer in the world was manufactured in late  
 163 1976 by Chisso-Asahi Fertilizer Company. This involved encapsulation of NPK fertilizers  
 164 inside a coat based on polyolefin, and the product is called “Nutricote”. In the same context,  
 165 the company SAG (Germany) developed polyurethane-coated NPK in 1982, under the trade  
 166 name “Plantacote”. Polyon [36] is a similar product that was developed in 1988 by Pursell  
 167 Industries, and it is based on the application of an ultra-thin polyurethane membrane coating.  
 168 The first application of biopolymers organic coating fertilizers was developed by Otey et al.  
 169 [37] and was based on starch as a coating material to produce controlled-release of urea  
 170 (starch-urea). The coating fertilizers with chitosan and alginate was not reported until 1990,  
 171 by Teixeira et al. [38]. In 1996, Garcia et al. [39] developed lignin-based controlled-release  
 172 coatings for urea fertilizers.

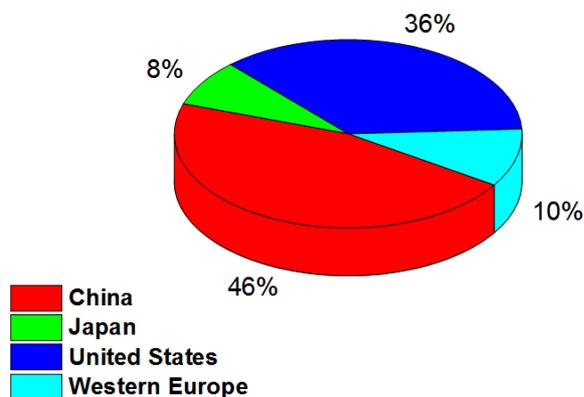


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**Fig.1.** Chorological development of CRFs/SFRs

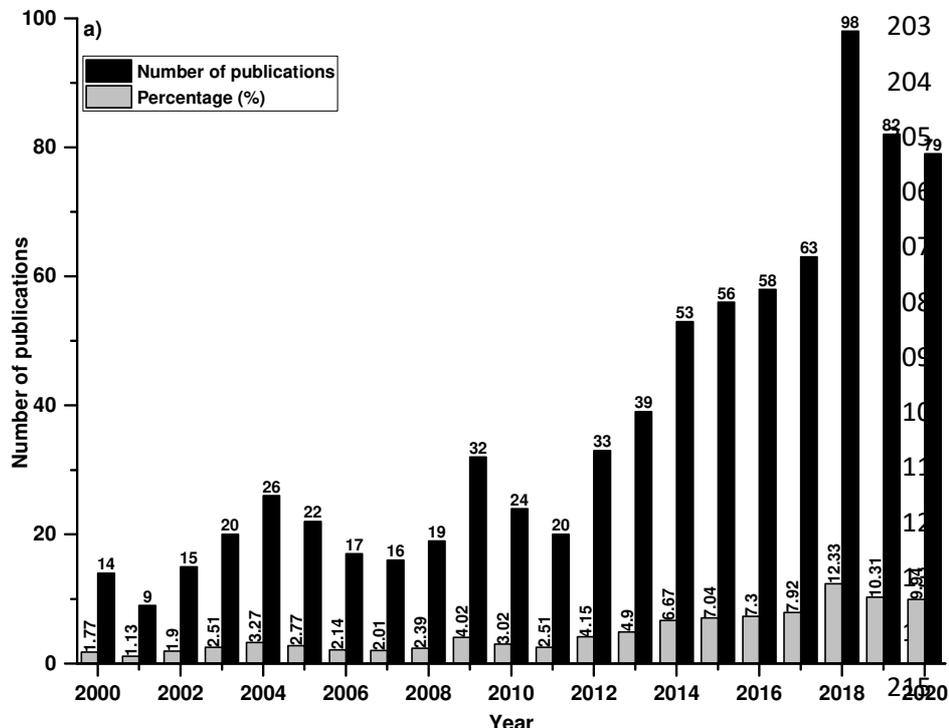
According to the IHS Markit Chemical Economics Handbook [40]: Controlled- and slow-release fertilizers Report, the global demand for SRFs/CRFs reached more than 1.5 million metric tons in 2018, and it is expected to grow by nearly 6% in 2022. In terms of consumption volume, China is the primary world market for slow- and controlled-release fertilizers, with a consumption rate of 46%, followed by the United States, Western Europe, and Japan [40] (Fig.2).



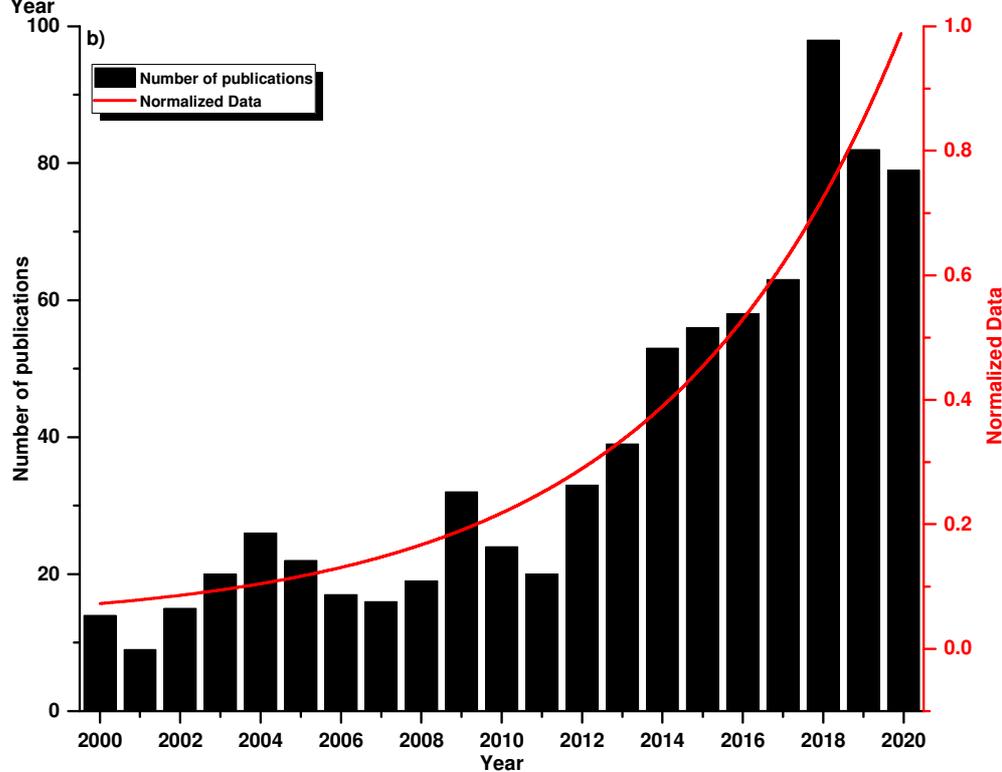
**Fig. 2.** Total consumption of Slow/Controlled Release Fertilizers in 2018 [40]

According to the Web of Science database, since 2000, 795 indexed research articles have been published using the keywords " Polymer coated fertilizers" ," Controlled release fertilizers" and "Slow release fertilizers" in title. According to the collected data (Fig. 3a) and the evaluation of keywords in terms of frequency, the keyword "Controlled release fertilizers" with its occurrence frequency of 389 ranked first, accounting for 48.2% of all global publications in this field, followed by "Slow release fertilizers" with 379 (47.7%) and then the keyword "Polymer coated fertilizers" with 33 (4.1%). Also based on this data, the publications related to the field showed significant growth from 14 in 2000 to 98 in 2018, and the number of publications continues to increase exponentially (Fig. 2b). This is a clear indication of the increase in the number of studies investigating this topic.

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231 **Fig.3.** a) Number of papers published between 2000 and 2020 involving keywords "Polymer  
232 coated fertilizers" or "Controlled release fertilizers" or "Slow release fertilizers", b)  
233 Normalized data by the total number of articles published in each analyzed year.

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235

### 236 **2.3. Advantages and disadvantages of SRFs/CRFs**

237 "Controlled Release Fertilizers (CRF)" and "Slow Release Fertilizers (SRF)" are both used to  
238 describe this new generation of fertilizer, but the two terms have different meanings. We  
239 believe that we cannot really control the release of a fertilizer, and that rather depends on the  
240 coating properties (i.e. composition, porosity, and thickness; solubility of the coating  
241 materials and the core materials, etc.); and soil properties (soil type, soil pH, temperature,  
242 moisture, microbial activities, etc.). However, to differentiate these two categories of CRFs  
243 are generally related to fertilizers coated or encapsulated with inorganic or organic matter.  
244 Polymer coated fertilizer is an example of CRFs. Concerning SRFs, they include plant  
245 manures, animal manures and compost that need to be broken down by microbial activity  
246 before the nutrients can be released. They also include UF, IBDU, and CDU [41]. In addition,  
247 CRFs allow a much more controlled rate and duration of nutrient release with semi-permeable  
248 coatings. While for SRFs, the duration of release in a slow release fertilizer cannot be  
249 controlled due to the effectiveness of microbial organisms. In this review we will use the term  
250 CRFs because we will focus on the coated fertilizers".

251 CRFs overcome numerous problems associated with conventional fertilizers in addition to  
252 presenting several advantages economically, environmentally, and physiologically.  
253 Nevertheless, CFRs also suffer from a number of disadvantages, and research should be  
254 intensified to address these problems. We will provide a detailed account of the main  
255 problems related to conventional fertilizers and the solutions provided by CRFs as well as the  
256 associated inconveniences.

257 - ***Environmental and health impact:*** Plants only consume part of conventional  
258 fertilizers and the rest is lost in the environment [42]. Approximately 40–70% of the  
259 nitrogen content is lost through leaching, mineralization, NH<sub>3</sub> volatilization, gas  
260 emissions (nitrous oxide NO<sub>x</sub>), soil erosion, and denitrification processes. In terms of  
261 phosphorous, 80–90% is lost due to surface run-off and mineralization (fixation of P  
262 and formation of Fe- and Al-based oxides), and 50–70% of the potassium is lost

263 mainly by leaching associated with water movement in the soil and surface run-off  
264 [43]. In addition to the economic loss, this high level of nutrient loss also gives rise to  
265 environmental issues. Nitrates from nitrogen fertilizer sources can contaminate  
266 groundwater by leaching and accumulation from agricultural activities, which can  
267 cause serious and immediate effects on human health because of the consequent  
268 deterioration of the quality of drinking water. N volatilization also pollutes the air and  
269 gives rise to adverse atmospheric effects and hazardous emissions, with consequent  
270 dermal irritation and inhalation problems. Phosphorus overflow gives rise to the  
271 eutrophication phenomenon in freshwater and estuaries; which overstimulates the  
272 growth of algal blooms and contributes to a wide range of water-related problems  
273 including summer fish kills, foul odors, and unpalatable tastes in drinking water.  
274 Excessive fertilizer use can negatively affect soil quality through acidification,  
275 persistent organic pollutants, and heavy metal accumulation [6]. CRFs have the  
276 potential to reduce the nutrient losses, as well as to minimize the potential negative  
277 effects and the risk of environmental pollution described previously and associated  
278 with overdosage [44]. Despite their positive effects, CRFs can also result in a number  
279 of negative effects that merits to be addressed. The main problem with CRFs is the use  
280 of slowly or non-degradable materials. Some types of polymers used in the coating are  
281 degraded extremely slowly or not at all in soil. Their use may lead to an undesirable  
282 accumulation of plastic residues, up to 50 kg/ha/yr, and 500 kg/ha takes almost ten  
283 years to be decomposed to just 200 ppm of dry soil [1,7,26,29,44]

- 284 - ***Agronomic effect:*** CRFs have agronomic advantages related to the improvement of  
285 plant growth conditions. These enhanced-efficiency fertilizers slowly release the  
286 nutrients to match with the plant nutrient demands and to ensure synchronization with  
287 crop requirements. Additionally, plants derive an advantage from the fertilizer due to  
288 the absence of osmotic stress or the burning of roots and leaves caused by the high  
289 concentration of soluble salts with conventional fertilizers. Further possible benefits  
290 are that CRFs improve the soil quality and germination rates while also reducing stalk  
291 breakage and disease infestation. CRFs can increase nutrient availability and the  
292 accumulation of proteinaceous material in plants, thereby resulting in higher yields  
293 [26].
- 294 - ***Economic impacts:*** By reducing nutrients loss, CRFs can generate savings in terms of  
295 the quantity of the fertilizer. A decrease of 20 to 30% of the recommended application  
296 rate of a conventional fertilizer is possible when CRFs are used, while still

297 maintaining the same yield [26]. Savings can also be achieved in terms of the labor,  
298 time, and energy involved. Indeed, a single application of CRFs can meet crop nutrient  
299 demands for an entire season, thus reducing the application frequency and providing  
300 savings in regard to the spreading costs [26]. Additionally, the storage and handling of  
301 CRFs are also more convenient. However, the manufacturing cost of most coated or  
302 encapsulated CRFs is still considerably greater than that of conventional mineral  
303 fertilizers due to the price of the materials and the process, although these expenses  
304 can largely be compensated by the gains mentioned above.

### 305 **3. CRFs based on biopolymers (CRF@BB) and biodegradable polymer coatings**

306 In this review, we focus on the coating of mineral fertilizers based on biopolymers and  
307 biodegradable polymers, referred to as “biofertilizers based on biopolymers (CRF@BB) and  
308 biodegradable polymers coatings”.

#### 309 **3.1. Biopolymers and biodegradable polymers used as organic coatings for CRFs**

310 There is a lack of consensus regarding the definition of a biopolymer; some researchers define  
311 it as a polymer derived from biomass, produced by living beings (plants, algae, animals,  
312 fungi, etc.). Others say that every biodegradable, biocompatible, and nontoxic polymer can be  
313 considered to be a biopolymer, even if it is generated by synthetic means, e.g., polylactic acid,  
314 PLA [45]; polyvinyl alcohol, PVA [46,47] polybutylene succinate, PBS [48]; and  
315 polydopamine [49]. Throughout this review, we use the term ‘biopolymers’ to mean polymers  
316 derived from naturally available and renewable resources, i.e., starch [50], lignin [51,52],  
317 cellulose derivatives [53–55] chitosan [56–59], carrageenan [60], guar gum [61], xanthan gum  
318 [62], natural rubber [63], etc.

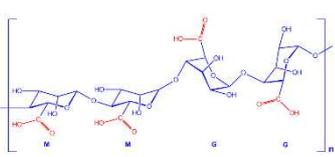
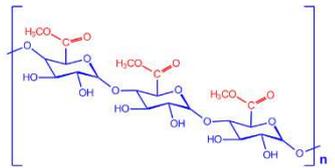
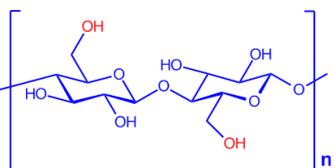
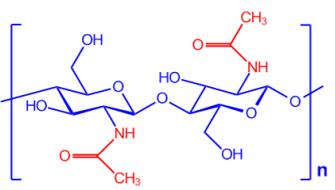
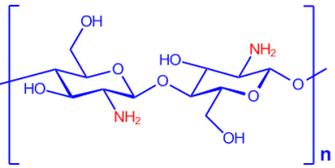
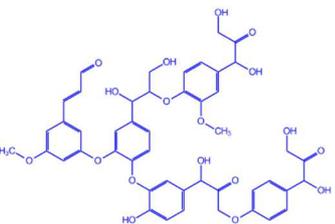
319 Biopolymers are known for their relatively cheap price compared to the synthetic polymers  
320 used as conventional coating materials, which depend greatly on the extraction and  
321 purification methods employed [64]. Biopolymers also have a number of other advantages:  
322 biodegradability in soil and nontoxicity [65,66], a good soil water-holding capacity, reduced  
323 oxidative stress, enhanced particle aggregation, and minimal soil erosion. Biopolymers can  
324 also be used directly as a soil amendment [67] and to stimulate the dormant microbial activity  
325 [68].

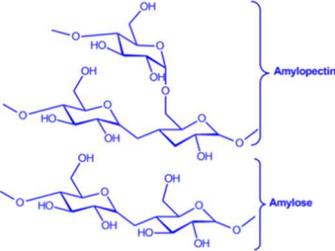
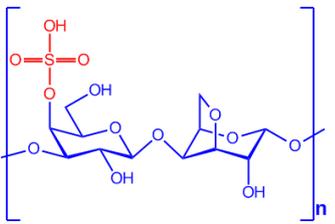
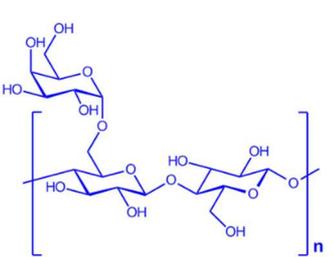
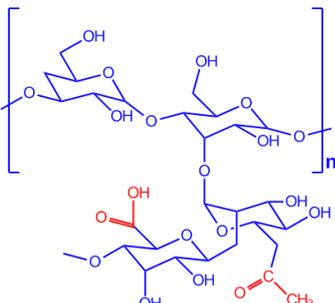
326 The most commonly used biopolymers with CRFs, their biomass origins and extraction  
327 methods and their chemical structures are presented in Table 1. Theses information are  
328 essential for choosing an adequate biopolymer, which depends on its availability, the

329 extraction and purification method, and a number of key physicochemical properties that are  
330 useful in CRFs production. Some studies have reported that the release longevity of lignin,  
331 cellulose, and starch-coated fertilizers is too short [64]. Cellulose and starch are hydrophilic  
332 polymers due to the presence of hydroxyl groups (-OH) on their surface, and starch has poor  
333 mechanical properties. Lignin is comprised of heterogeneous biopolymers, it is insoluble in  
334 water, and it is incompatible with hydrophilic polymers such as chitin and cellulose, which  
335 are highly crystalline [1,69]. Overcoming such limitations is of considerable relevance, and  
336 these are the reason why, for biopolymers to be useful, they need to undergo a degree of  
337 chemical and physical modification. For instance, chitin can be modified by deacetylation,  
338 thereby converting it into chitosan [70], which has remarkable solubility and film-forming  
339 properties. Other researchers often incorporate crosslinkers [71–73], compatibilizers [20], and  
340 plasticizers [74–77] in the coating solutions. These added elements change the flexibility,  
341 tensile strength, and adhesion properties of polymeric membranes [74,77]. Blending and  
342 copolymerization of different biopolymers or biopolymers with synthetics has also become of  
343 interest, and these have been the subject of several studies. Researchers have tested various  
344 possibilities: natural rubber and starch [78], lignin and ethyl cellulose [79], starch with lignin  
345 [80], starch and polyvinyl alcohol [81,82], starch with poly(L-lactide) [83], sodium alginate  
346 and poly(acrylic acid-co-acrylamide) [84], starch and poly(acrylic acid-co-acrylamide) [85],  
347 chitosan with poly(acrylic acid) [86], guar gum and poly(acrylamidoglycolic acid) [87], starch  
348 and poly(vinyl acetate- co-butyl acrylate) [88], starch and poly(acrylic acid) [89], and sodium  
349 carboxymethyl cellulose with hydroxyethyl cellulose [90].

**Table 1**

The most commonly used biopolymers as coatings, their structure, origins, and some of the extraction methods

Biopolymer	Structure	Origins	Extraction methods
Alginate		-Brown algae	-Seaweed powders were treated many times with a 2% aqueous solution of CaCl <sub>2</sub> , HCl 0.01M, pH 2, for 3 hours at 70 °C with mechanical stirring), centrifuged, solubilized in Na <sub>2</sub> CO <sub>3</sub> (3%) and recovered after dialysis [91].
Pectin		- Primary cell walls and the middle lamella of higher plants (citrus peel, apple pomace, and sugar beet pulp) [92]	-Boiling of an aqueous solution of HNO <sub>3</sub> under various conditions in a heating mantle with a reflux system. After centrifugation (5000 rpm, 20 min, 4 °C), the supernatant was filtered and precipitated with absolute ethanol 1:2 (v/v) [93].
Cellulose		-Crop plants, wood, cotton, algae, and biomass wastes [94]	- Dispersion of dry powder in water at 2% (w/v). After centrifugation (2500 rpm, 30 min), a sodium hydroxide solution 4wt% was added to the resulting pellet (80 °C, 2 h, and 150 rpm). This treatment was repeated, and the sample was washed thoroughly with water, centrifuged, and then dried at room temperature [94].
Chitin		-Invertebrates (crustacean shells, insect cuticles...), fungi, green algae, cell walls, and yeasts [95]	-Chemical extraction comprising 3 steps: *Deproteination (0.125 to 5 M NaOH, at various temperatures and treatment duration. *Demineralization (0.55-1.5 M HCl, 35-50 °C, 30 min-6 h) * Discoloration (an organic solvent mixture or acetone to eliminate pigments) [96].
Chitosan			-Deacetylation of chitin (concentrated NaOH solution for a few hours) [96].
Lignin		-Lignocellulosic materials (agricultural residues, wood) [97]	-Fractionation process (ternary mixture solvent (methyl isobutyl ketone, ethanol, and water (25, 42, and 33% v/v) in the presence of H <sub>2</sub> SO <sub>4</sub> 0.025 M. The reaction was carried out at different temperatures (140, 160, 180 °C), 40 min, N <sub>2</sub> (20 bars), and 100 rpm. The reaction was stopped by quenching on ice (10 min), the mixture was then filtered and the solid fraction was washed with distilled water (neutralization to pH 6-7) [97].

Starch		-Maize, Wheat, Rice, Cassava [98]	-H <sub>2</sub> SO <sub>4</sub> (0.15% w/w, 16 h at room temperature) followed by centrifugation (5000 rpm, 10 min), washed with anhydrous ethanol and acetone, and dried at 40 °C [98].
Carrageenan		-Red algae	-Seaweed was mixed with KOH (6% w/v), and the reaction was carried out at 80 °C for 3 h. The slurry was then filtered and the carrageenan in the permeate were precipitated with 80% isopropanol, filtered, and recovered by freeze-drying [99].
Guar gum		-Seeds	-Crushed seeds were immersed in NaCl solution (5%, pre-adjusted to pH 3 with acetic acid) for 24 h at 50 °C and 300 rpm. The mixture was sieved, treated with (90% ethanol and 10% isopropanol), centrifuged (6000 rpm, 7 min). The thereby obtained gum was then dissolved in clean water, precipitated with 90% ethanol and 10% isopropanol, filtered, and dried at 50 °C [100].
Xanthan gum		-Xanthomonas bacteria	-Fermentation of glucose by various species of Xanthomonas bacteria [101].

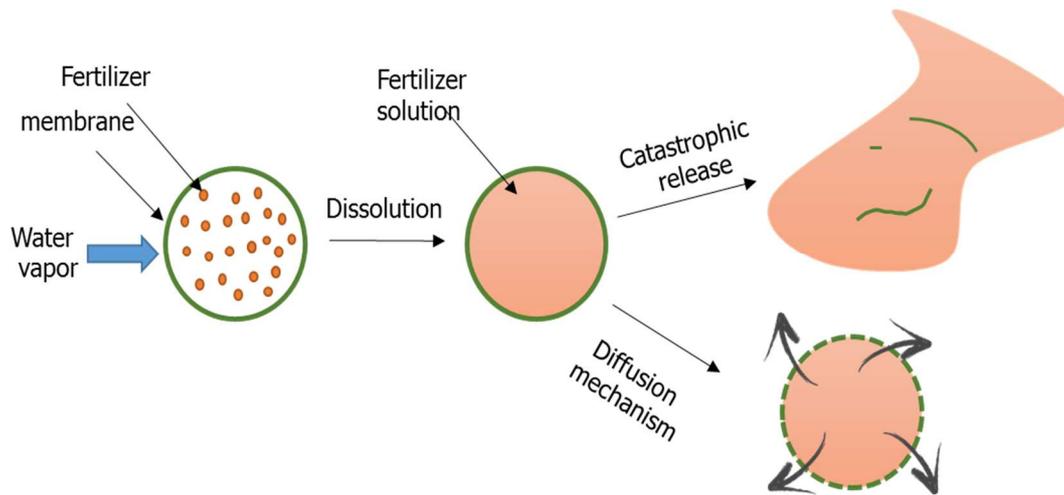
350

### 351 3.2. Slow-release mechanisms of CRF@BB

352 The nutrient release behavior and rate are the most important properties for CRFs. To test the  
353 release rate of nutrients from coated fertilizer, most authors have generally used water[102–  
354 106], soil [107,108] or both systems [109,110], while a small number have used saline  
355 solutions [111]. Most researchers choose distilled water as the environment for release testing.  
356 This is related to the large differences encountered in regard to soil properties and climate  
357 conditions. Therefore, they typically use distilled water, which is a valid and readily available  
358 release environment for comparing results. However, the release behavior in water is not  
359 similar to that in soil. Vudjung et al. [63] claimed that coated urea released 100% of nitrogen  
360 within 24 days in soil, whereas the release rate of nitrogen in water was very fast (100% in 3  
361 days). El Assimi et al. [109] and Baki et al. [112] have confirmed this result. According to

362 Baki, the release rate of nitrogen through the coated fertilizer was lower in soil than water;  
363 approximately 60% were released in soil after 30 days, while in water, approximately 35%  
364 were released within 10 days. This result is not in keeping with the results reported by Jia et  
365 al. [113]. These authors showed that the release rates of  $P_2O_5$ , Cu, and  $K_2O$  through coated  
366 fertilizer in soil were slower than in water, whereas the release rate of nitrogen was faster in  
367 soil than water. This complexity and heterogeneity of the different studies regarding the  
368 release of NPK (in water, soil, etc.) complicates the determination of the release mechanisms.  
369 However, several researchers claim to have identified and understood the controlled-release  
370 mechanism from coated fertilizers at different stages. It is not easy to establish the mechanism  
371 of release, which depends on many factors: the coating and soil properties. In this section, we  
372 do not discuss coated fertilizer/soil interactions. Rather, we focus only on the release  
373 mechanisms of nutrients through the polymeric coating materials in water and in soil  
374 solutions. Morgan [114] reported that polymer-coated materials release nutrients by diffusion  
375 through a semi-impermeable membrane. Shaviv [27] and Liu [115] developed a now well-  
376 known model called the “multi-stage diffusion model”, in water. According to this model, the  
377 coated fertilizer has to come into contact with water in order to liberate its nutrients. In the  
378 first stage of the release process, the water penetrates through the coating membrane and it  
379 condenses on the solid core, which is followed by partial nutrient dissolution. Due to this  
380 dissolution, internal pressure (or osmotic pressure) builds up in the granule, which then swells  
381 up. Two phenomena may take place as a function of the membrane resistance and the internal  
382 pressure. If the membrane resists the osmotic pressure, the core fertilizer releases slowly by  
383 diffusion, which is called the diffusion mechanism, and it is determined by the concentration  
384 gradient across the coating, or by the pressure gradient, or by both gradients. However, if the  
385 internal pressure surpasses the membrane resistance, the “failure mechanism” or “catastrophic  
386 release” occurs, whereby the entire content is released due to rupture of the coating material  
387 followed by bursting of the granule (Fig.4). Catastrophic release usually occurs with frail and  
388 non-elastic coatings such as sulfur-based coatings. Moreover, biopolymer-coated fertilizers  
389 are known for their slow-release mechanism [116]. Interactions between the fertilizer granule  
390 and the polymer layer are physical rather than chemical [117]. Wu et al. [5] proposed a model  
391 of the release mechanisms of nutrients in soil from polymeric coated fertilizers, especially  
392 from double-coated fertilizers with a superabsorbent outer coating. In the first step, the layer  
393 slowly swells by the soil solution and then transforms into a hydrogel. A dynamic exchange  
394 between the free water in the hydrogel and the water in the soil occurs, after which the free  
395 water in the superabsorbent layer migrates to the middle layer, and water then slowly

396 penetrates through the inner coating in the initial stage and compounds in the fertilizer  
397 become dissolved. In this stage, diffusion is the rate-limiting step in the release. Under the  
398 effect of water, ions, and microorganisms present in the soil, the middle layer slowly degrades  
399 in the last stage and the nutrients continue to dissolve. In this stage, the degradation rate  
400 determines the nutrient release rate. Finally, the dissolved fertilizer components diffuse out of  
401 the middle layer and enter into the outer layer so that they are then released into the soil by the  
402 dynamic exchange of free water.



403  
404 **Fig.4.** Release mechanisms of nutrients through a polymeric coating when in contact with water (or  
405 soil solution)

### 406 3.3. Coating parameters that control nutrient release

407 There are many factors that affect the release rate of nutrients through these polymer-based  
408 coatings. The most important parameters are: the nature of the polymer (hydrophilic or  
409 hydrophobic), their concentration in the coating solution, the solution viscosity, added  
410 modifying agents, the number of layers, and the techniques used for the coating (Table 2). All  
411 of these parameters influence the thickness and the porosity of the coating layer [118]. These  
412 parameters are interdependent and govern the nutrient release rate [19,20,74,118–120]. They  
413 are discussed in detail below.

#### 414 3.3.1. Coating methods

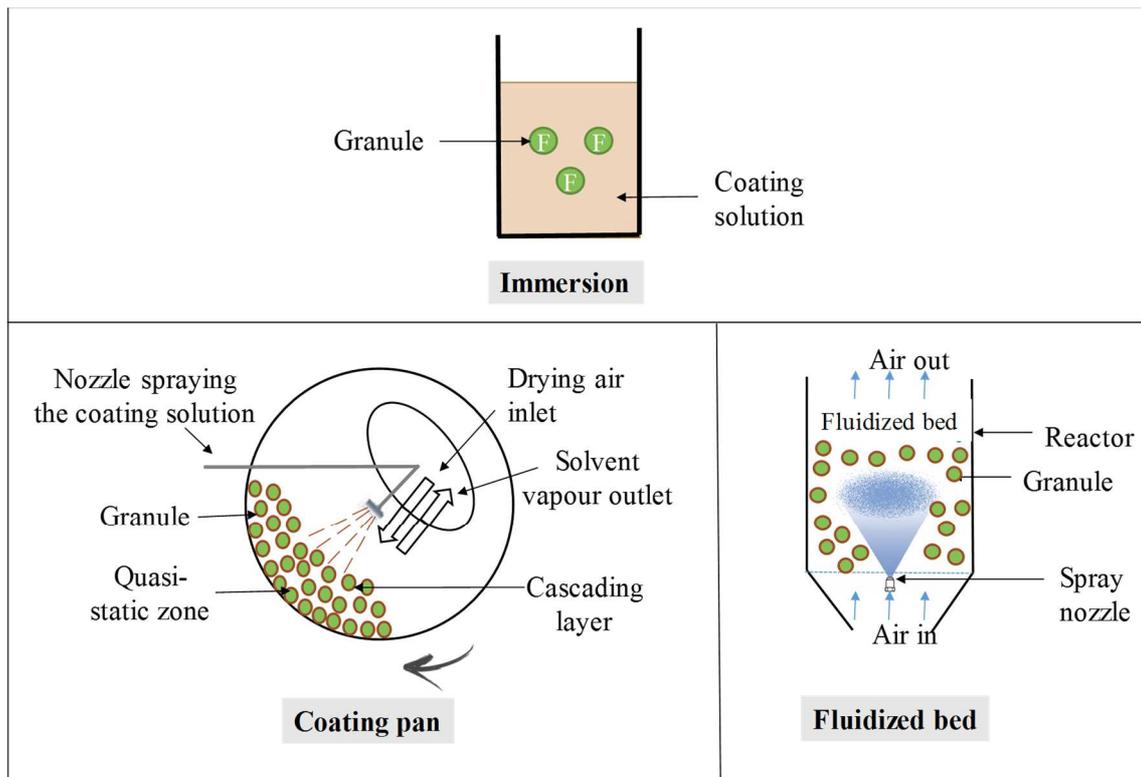
415 The coatings of granular fertilizers can be applied by various methods such as spraying of a  
416 liquid, dipping into a liquid, precipitation from supercritical fluids, or by deposition of a  
417 powder using an electrostatic technique [121]. The most commonly used techniques for  
418 coating fertilizers are: immersion and spraying a liquid onto the substrate (Fig.5). Spraying is  
419 commonly carried out either in a coating pan (rotary drum) or a fluid bed coater [122].

420 **Immersion:** realizes by dipping the fertilizer into the polymer coating solution [2,123]. The  
421 solution adheres to the granule surface of fertilizers and fixed by a drying system.

422 **Coating pan:** This is one of the most commonly used techniques to coat fertilizer granules  
423 with polymeric solutions. The coating liquid is transferred as a spray to the surface of the  
424 beads already present in the spray zone. The system employs an air-atomizing spray nozzle at  
425 the center of the drum to spray the coating solution and a hot air stream to evaporate the  
426 solvent and then dry the coated particles. The coating is carried out by two systems; the first  
427 one is a cascading layer composed of a thin layer of granules that flows down the free surface,  
428 and the second one is a quasi-static zone comprised of the remaining granules that rotates as a  
429 fixed bed. As the pan rotates, the beads cascade through the spray zone under gravitational  
430 force. The granules come into contact with the spray and they become coated with the coating  
431 solution, followed by drying, before moving into the bulk of the tablet bed. After a period of  
432 circulation, the beads may re-enter the spray zone and the coating and drying process are  
433 repeated. The granule residence time at the surface of the cascading bed determines the  
434 quantity of solution received by a granule per pass through the spray zone. The quality and  
435 performance of a coating are influenced by several parameters: simultaneous exchanges of  
436 heat and mass between the coater pan and the inlet air stream, the spraying material and  
437 substrate, the dimensions, the rotational speed, the configuration and the number of baffles,  
438 pan loading, the bed humidity, and the pan coater temperature [124,125]

439 **Fluidized bed (Wurster):** This is used to coat solid granules such as pellets, granules, or  
440 powders. It is widely used in the pharmaceutical, food, feed, and fertilizer industries [126].  
441 Fluidized beds are based on the fluidization of the initial granules by hot air, while a  
442 suspension or solutions are sprayed onto them. There are three commonly used configurations  
443 of fluidized bed; top spray, bottom spray, and side spray. In regard to the coating of fertilizers,  
444 a Wurster fluidized bed, which is a modified bottom-spray fluidized bed, is the most suitable  
445 apparatus to coat fertilizers. This configuration is characterized by a bottom-spray nozzle and  
446 a Wurster tube located in the center. Due to this special design, the granules are forced to  
447 follow a circulating flow trajectory [127,128]. The key variables that control this coating  
448 process are classified according to three aspects; the first one relates to fluidization, which is  
449 controlled by the input air flow rate, the dimensions and type of the equipment, the particle  
450 size and density, the substrate surface characteristics, and the batch size. The second one  
451 relates to the coating. It is determined by the position and the design of the nozzle, the droplet  
452 size, the viscosity, the surface tension and density, the injection pressure, atomizing air, as

453 well as the coating liquid flow rate. The third aspect comprises the drying parameters,  
 454 including the inlet and outlet temperature, as well as inlet air flow rate and the air humidity  
 455 [129,130].



456  
 457 **Fig.5.** The most commonly used techniques for coating fertilizer granules

458 The coating methods affect the quality of coatings, which is a key parameter to control the  
 459 nutrients release behavior. With immersion, the fertilizer granules can be partially dissolved  
 460 because they are dipped into the coating solution, especially water-soluble fertilizers. The  
 461 granules can also stick to each other if the solution is very viscous and the coating is generally  
 462 damaged when they are separated after drying. Use of the rotating pan method is a good  
 463 alternative for immersion. The coating parameters for a rotating pan impact the coating  
 464 quality (dimensions, rotational speed, spray flow rate, etc.). Generally, the rotating pan  
 465 method minimizes mechanical damage of the beads and it reduces the level of attrition  
 466 because the granules are moved in a gentle manner. Consequently, the coated layer is  
 467 damaged less by the coating process. However, it is not easy to achieve a uniform thickness  
 468 for the coated layer for the entire fertilizer batch unless large amounts of the coating materials  
 469 are used. The limited coating uniformity and the higher product variability affect the nutrient  
 470 release rate. The release will not be uniform through the coating of the granules  
 471 [121,122,126,131]. With the fluidized bed method, the layer thickness is uniform, with a

472 precise degree of film coating. Nevertheless, aggressive granule movement results in a high  
473 level of mechanical stress on the beads, and the attrition can affect the quality of the coatings  
474 and consequently the release behavior through these coatings [5,121,131,132].

### 475 **3.3.2. Coating formulation properties**

476 Formulation is a key parameter that governs the release behavior of nutrients. It depends on  
477 the components and their compatibility, their hydrophilic or hydrophobic nature, and their  
478 concentrations in the solution and the viscosity.

479 **Hydrophobicity**: The hydrophobic/hydrophilic nature of the formulations used in the  
480 preparation of the coating is a crucial parameter for the release behavior of nutrients. When  
481 the coating material is hydrophobic, the affinity between the layer and water is weak. This  
482 lack of affinity prevents the penetration of large quantities of water into the fertilizer core and  
483 it decreases the dissolution [19]. Jarosiewicz et al. [19] showed that the release rate of  $\text{NH}_4^+$  is  
484 three times faster when hydrophilic polyacrylonitrile is used as the coating for nitrogen  
485 fertilizer compared to hydrophobic polysulfone.

486 **Component compatibility and modifying agents**: The compatibility between components  
487 affects the coat-forming quality. If the components are not compatible, two or more phases  
488 could arise in the same coating, which would result in a non-homogeneous film that could  
489 exhibit cracks and pinholes. In most coating formulations; plasticizers, crosslinkers, or  
490 compatibilizers are added to improve the mechanical and adhesion properties of polymeric  
491 membranes [74,77,133]. When these properties are adequate, the shell can resist the internal  
492 pressure created inside the core in contact with water, and the nutrients are then released  
493 slowly without the shell being destroyed. Niu et al. [134] reported that the presence of  
494 plasticizers slows the release of ammonium nitrate. They suggest that this is related to the  
495 formation of films without cracks when plasticizers are added, which decrease the  
496 permeability of water and slows the release of nutrients. Blending, grafting, and  
497 copolymerization of different biopolymers, or biopolymers with synthetics, are also used to  
498 produce good coatings. Coating of urea with natural rubber reinforced by grafting with  
499 modified cassava starch (NR-g-ST) has been reported by Riyajan et al. [120]. Capsule coating  
500 with only starch resulted in almost 100% N release within 8 h. With the NR-g-ST coating, the  
501 capsule N release was only 21% within 1 day. This decrease in the N diffusion rate could be  
502 related to the chemical interaction between natural rubber and starch via grafting interaction.

503 **Polymer concentration**: The release rate of nutrients also decreases as the polymer  
504 concentration in the coating solution is increased. Indeed, higher polymer concentrations

505 result in a greater thickness and lower porosity in the coating layers of fertilizer granules. Nui  
506 et al. [134] showed that coating formulations with 10% ethyl cellulose in the coating solution  
507 produce layers on coated urea that are less thick (49  $\mu\text{m}$ ) compared to 70  $\mu\text{m}$  with 20%. The  
508 release of N through the thick layer was slower than for the thin layer. These results are in  
509 good agreement with those of Pérez et al. [135] who argued that the release of N from an  
510 ethyl cellulose-coated granule depends on the polymer concentration in the formulation. As  
511 expected, a high concentration of polymer increased the thickness of the coating film and  
512 slowed the release of N. The polymer type and its concentration also affect the porosity of the  
513 coating. The coatings formed from solutions with a higher polymer concentration exhibited  
514 reduced porosity [19], and consequently the release rate of nutrients decreased.

515 ***Viscosity:*** Solution viscosities that are too low or too high can result in an incomplete or  
516 damaged coating layer, or they can induce dissolution of water-soluble fertilizers in case of  
517 solutions with very low viscosities. Jarosiewicz et al. [19] reported that the viscosity of film-  
518 forming solutions increases as the polymer concentration increases. This causes an increase in  
519 the thickness and a decrease in the porosity as well as in the release rate of nutrients.

### 520 **3.3.3. Number of coating layers**

521 Fertilizer granules can be coated by one [136] or several layers [137,138] using the same  
522 coating solution. They can also be coated by two [109,138–141] or three layers [142] of  
523 different solutions, and by the same or different coating techniques. Single and double layers  
524 are the most common. In the case of double and triple layers, the second layer is generally  
525 superabsorbent.

526

527 ***NPK granules with a single coating:*** A single layer is made using one of the techniques  
528 mentioned in Section 3.3.1. Multiple layers are obtained by coating the fertilizer granule and  
529 drying it before re-coating until the desired number of layers is obtained. Generally, multiple  
530 layers using the same solution are obtained using the immersion technique. The granules are  
531 dipped once, twice, or several times in the same coating solution. Messa et al. [143]  
532 developed a chitosan-based formulation to coat NPK fertilizer with a single coating. They  
533 found the chitosan coating provided a reduction in the initial release rate of NPK, 100% of  
534 NPK was released in water from coated fertilizer within 2 hours compared to 100% within  
535 less than 20 min from uncoated fertilizer. Ahmed et al. [144] also prepared a chitosan-coated  
536 phosphorus fertilizer, but they studied the effect of the number of layers on the release rate of  
537 P. Compared to a single layer (63  $\mu\text{m}$ ) of coating film, the thickness of the double and triple-

538 coated films was approximately 1.5 (96  $\mu\text{m}$ ) and 2 (128  $\mu\text{m}$ ) times higher, respectively. The  
539 average thickness of the coating film increased as the number of coatings increased. The  
540 release rate of P was lower with the triple-coated granules than with the single-coated  
541 granules, thus revealing the effect of thickness on the P release behavior. Jarosiewicz et al.  
542 [19,119] also reported that coated NPK granular fertilizer based on cellulose acetate and a  
543 modifying agent (formamide) released nutrients rapidly after 5 h and that the slowest release  
544 of macroelements was achieved with a double coating of 18% polymer solution with 5%  
545 formamide in the casting solution. They showed that NPK coated with a single layer of 17%  
546 polyacrylonitrile solution released 97.3% of the K compared only to 11.7% with three layers  
547 of the same solution.

548

549 ***NPK granules with double coatings:*** For double layers with different coating solutions, the  
550 aim is to ensure several properties using multiple layers. The first layer is generally intended  
551 as a physical barrier to impede the release of nutrients, and the second layer is a  
552 superabsorbent entity capable of absorbing water and releasing it when the plant needs it.  
553 These are multifunctional fertilizers that are particularly useful in arid zones. The multiple  
554 layers increase the coating thickness and decrease its porosity as well as the release rate due to  
555 a more compact structure of the coating and a lower porosity compared to a single coating  
556 [19]. Wi et al. [145] developed a double-coated slow-release NPK compound fertilizer with  
557 chitosan as the first layer and poly(acrylic acid)/diatomite – containing urea – as the  
558 superabsorbent second layer. The release rate of N, P, and K through this coated fertilizer was  
559 in the range of 2.3-11.9% in 3 days and 64-73.2 % in 30 days. These release rates are much  
560 slower than that of uncoated fertilizer, which released more than 80% and 87% within only 2  
561 and 5 days, respectively. Ni et al. [146] developed a multifunctional slow-release fertilizer  
562 using a matrix of NPK fertilizer with natural attapulgite clay as the core, sodium alginate as  
563 the first layer, and sodium alginate grafted to poly(acrylic acid-co-acrylamide)/humic acid  
564 superabsorbent polymer as the second layer. The release rate of N from the untreated fertilizer  
565 in soil was 98.5% in 12 h [147], while the same percentage was released through the coated  
566 fertilizer in 30 days. Xie et al. [28] reported a double-coated slow-release NP fertilizer with a  
567 wheat straw/sodium alginate blend as the inner coating and poly(acrylic acid-co-N-  
568 hydroxymethyl acrylamide)/wheat straw superabsorbent composite as the outer coating. The  
569 release of N from the coated fertilizer in soil was less than half (40.3%) of the release rate of  
570 the untreated fertilizer. The release of P was only 42.6% in 30 days from the coated NP  
571 compared to 66.2% in 5 days from the uncoated fertilizer. Wang et al. [148] developed a

572 multifunctional N slow-release fertilizer by coating granules of nitrogen using k-carrageenan-  
573 sodium alginate (k-SA) and cross-linked k-carrageenan grafted to poly(acrylic acid)/celite  
574 superabsorbent as the inner and outer coating materials, respectively. The release rate of  
575 nitrogen from the coated fertilizer was 94% within 25 days, which was much slower than the  
576 uncoated nitrogen fertilizer, which was reported to release 98.5% of the N in 12 h [147]. The  
577 same authors have developed a slow-release fertilizer (NPK) based on natural attapulgite clay  
578 as a matrix, guar gum as an inner coating, and guar gum grafted to poly(itaconic acid-co-  
579 acrylamide)/humic acid superabsorbent polymer as an outer coating. The release rates for N,  
580 P, and K through the core (NPK +attapulgite) in soil were fast; 100% in 5 days for N, and  
581 93.3% and 94.2%, for P and K, respectively, in 30 days, while the release rates through the  
582 double-coated fertilizer were 100% in 20 days for N, and 88.2% and 92.4% for P and K,  
583 respectively, in 30 days. Of note, the release rate of nitrogen was the highest, while the release  
584 rate of P was the slowest, which is in agreement with the findings of Wu et al. [5]. To explain  
585 this, the ionic mobility and the electronic and steric effects of  $K^+$  and  $NH_4^+$  ions were  
586 compared. The ionic mobility of  $NH_4^+$  and  $K^+$  are very similar ( $1.000$  and  $1.001 \text{ m}^2 \text{ s}^{-1} \text{ V}^{-1}$ ),  
587 and they also have the same positive charge value. However, the size of  $K^+$  ( $1.33 \text{ \AA}$ ) is  
588 smaller than that of  $NH_4^+$  ( $1.47 \text{ \AA}$ ), and  $K^+$  ions have a higher surface area charge density to  
589 interact with the negatively charged carboxylate ion of the hydrogel layer [142] and hence  
590 spread more slowly [5]. Lü et al. [77] investigated an environmentally friendly entity of N  
591 mixed with natural attapulgite as the core, starch acetate as the inner coating, and  
592 carboxymethyl starch/xanthan as the outer coating. The release rate from the uncoated  
593 fertilizer was 79.9% in 1 day, while it decreased to 56.5% by coating the fertilizer with starch  
594 acetate only. Addition of the second layer (carboxymethyl starch/xanthan gum) doubled the  
595 time taken to release 100% of the N from five to ten days. Wang et al. [149] developed a  
596 biomass-based multifunctional controlled-release fertilizer. This fertilizer was based on  
597 natural attapulgite, ammonium zinc phosphate, and urea, while cellulose acetate butyrate  
598 (CAB) and carboxymethyl chitosan-g-poly(acrylic acid)/attapulgite superabsorbent composite  
599 were the inner and the outer coating, respectively. The release rate of N by the untreated  
600 fertilizer in soil was 98.5% in 24 h. After coating, 9.2, 53.1, and 81.4% of the N was released  
601 within 3, 15, and 30 days, respectively. The release of Zn from the coated fertilizer was lower  
602 than N; only 41.2% of the Zn was released within 30 days. Mingyo et al. [150] reported the  
603 production of a slow-release membrane-urea fertilizer. The first layer was starch and the  
604 second layer was acrylic acid and acrylamide. The release rate of N in soil from just the

605 fertilizer was more than 85% in 2 days. However, when the fertilizer was coated with starch  
606 and acrylamide, the release rate decreased more than 8-fold.

607

608 ***NPK granules with triple coatings:*** Triple coating of fertilizer is achieved by coating the core  
609 using the first solution, and then waiting for it to dry before applying the second followed by  
610 the third coating solution. However, only a limited number of studies have been undertaken  
611 using three layers from different coating solutions. Noppakundilograt et al. [142] developed a  
612 trilayered controlled-release NPK fertilizer hydrogel by dipping the NPK fertilizer granules  
613 into poly(vinyl alcohol) (PVA) to form the first layer. After drying, the PVA-coated fertilizer  
614 granules were immersed in a chitosan solution and the PVA-chitosan bilayer-coated fertilizer  
615 granules were then crosslinked in a closed system for 4 days. After this, the third layer was  
616 prepared by suspension graft copolymerization of acrylic acid (AA) and acrylamide (AM) to  
617 form poly(AA-co-AM). The results show that the coated NPK fertilizer did not fully  
618 dissolved in water within 30 days and that the total N release was the highest (83.9%)  
619 compared to P (62.3%) and K (36.2%).

620

**Table 2**

Fertilizers type, coating materials used, operating conditions and parameters of coating, and nutrient release rates

Reference	Coating materials	Fertilizer	Granule size (mm)	T coating (°C)	Contact time (min)	T drying (°C)	Drying time (min)	Coating method	Thickness (mm)	Release rate (%)
[63]	Natural rubber (NR)/Starch (ST)/ Wax (W)	N	3.6	100/Room temp	-	-	-	Rotary drum coater	0.108-0.193	* In water: - Urea beads: 100% in 2h - W/NR/ST blends: 100% in 72 h * In soil: - Urea beads: 100% in 72h - W/NR/ST blends: 100% in 576 h
[151]	Starch acetate/ glycerol/ polyvinyl alcohol biocomposites (SA/Gly/PVA)	Diammonium Phosphate (DAP)	-	90	-	60	240	Immersion	0.045-0.095	Nitrogen and phosphorus release: *In water: - Uncoated DAP: 100% of N in 1h35 and 100% of P in 1h20. -SA/Gly/PV- coated DAP (Single layer): 100% of N in 3h50 and 100% of P in 3h20. -SA/Gly/PV- coated DAP (Double layer): 100% of N in 5h and 100% of P in 4h30.
[109]	Chitosan-clay composite/Paraffin wax	DAP	2-4	50	-	Room temp	-	Immersion	0.02-0.06	Phosphorus release: * In water: - Uncoated DAP: 100% in 2h - Chitosan-clay/ Paraffin wax: 100% in 16h * In soil: - Uncoated DAP: 100% in 576h - Chitosan-clay/ Paraffin wax: 40% in 720h
[152]	Ethyl cellulose/cellulose-based superabsorbent	N	2-3	-	-	50	-	Rotating pan	-	Nitrogen release: * In soil: -Uncoated urea: 97% in 96h -Coated urea: 0.2, 15.1 and 58.6% in 96, 168 and 360h, respectively.
[153]	Ethyl cellulose	NPK	4-5	-	-	60	-	Immersion	0.204-0.244	Phosphorus release: * In water: - Uncoated NPK: 100% in 1h - Ethyl cellulose-coated NPK: 75% in 672h.
[56]	Chitosan (CS)/Graphene Oxide (GO) nanocomposites	KNO <sub>3</sub>	-	-	-	Air-drying	Overnight	Immersion	-	Potassium release: * In water: - Uncoated KNO <sub>3</sub> : 100% in 10min - CS-coated KNO <sub>3</sub> : 14% in 48h - Cs-GO-coated KNO <sub>3</sub> : 10% in 48h

[143]	Chitosan (CS)/Nanocellulose microparticles	NPK	0.002	95-180	-	Air flow	-	Spray dryer	0.563-0.682	* In water: -Uncoated NPK: 100% in < 20min -CS-coated NPK: 100% in 2h -CS/Nanocellulose-coated NPK: 100% in 5h
[138]	Poly (acrylic acid)-g-natural rubber NR-g-PAA	Urea/KH <sub>2</sub> PO <sub>4</sub>	1.3-1.5	-	-	-	-	Rotating pan/ Shaking with powder (Water atomization)	0.5	* In soil: -Uncoated fertilizer: 100% in 120h - NR-coated fertilizer: 69.44% of <b>N</b> , 69.28% of <b>P</b> and 66.94 of <b>K</b> in 720h. - NR-g-PAA coated fertilizer: 54.35% of <b>N</b> , 51.18 of <b>P</b> and 44.37% of <b>K</b> in 720h
[154]	Coco peat fibers-grafted-poly (acrylic acid) hydrogel	NPK	Dissolved in deionized water	60	-	60	Until constant weight	In-situ solution polymerization	-	* In water: - Uncoated NPK: 100% in 1h45 - Coco peat fibers-g-PAA-coated NPK: 38.1% in 3h and 100% in 840h (5weeks).
[53]	Sulfonated carboxymethylcellulose-g-Poly (AA)/ Polyvinylpyrrolidone/ Silica SCMC-g-PAA/ PVP/Silica	NPK	Dissolved in SCMC solution	60	4h	70	1440	In-situ polymerization	-	*In water: - Uncoated NPK: 100% in 6h -SCMC-g-PAA coated NPK: 89% in 1 month - SCMC-g-PAA/PVP coated NPK: 75.3% in 1month - SCMC-g-PAA/PVP/Silica coated NPK: 65.3% in 1month * In soil: Uncoated NPK: 100% in 4h -SCMC-g-PAA coated NPK: 83.6% in 1 month - SCMC-g-PAA/PVP coated NPK: 72.3% in 1month - SCMC-g-PAA/PVP/Silica coated NPK: 54.6% in 1month
[155,156]	Lignin/Carrageenan (LC) LC/Polyethylene glycol 200 LC/Polyethylene glycol	Triple superphosphate (TSP)	2-3	-	-	65	-	Rotating pan	0.218 ± 0.062	Phosphorus release in water: - Lignin/Carrageenan-coated TSP: 56% in 48h LC/PEG200-coated TSP: 65% in 48h LC/PEG2000-coated TSP: 79% in 48h

	2000									
	LC/Glycerol									LC/Gly-coated TSP: 71% in 48h
[116]	Lignin	Triple superphosphate (TSP)	2-3	-	-	65	-	Rotating pan	0.0713±0.0236	Phosphorus release in water: -Uncoated TSP: 99.5% in 72h - Lignin-coated TSP: 76% in 120h
	Alginate									- Alginate-coated TSP: 75.3% in 120h
	Carboxymethyl cellulose									- Carboxymethyl cellulose-coated TSP: 73.7% in 120h
	Carrageenan									- Carrageenan-coated TSP: 90.2% in 120h
	Lignin/ Alginate									- Lignin/ Alginate-coated TSP: 64.9% in 120h
	Lignin/ Carboxymethyl cellulose									- Lignin/ Carboxymethyl cellulose-coated TSP: 59.2% in 120h
	Lignin/ Carrageenan									- Lignin/Carrageenan-coated TSP: 75.3% in 120
[52]	Lignin/montmorillonite (L/MMT)	Urea	Extruded urea/MMT (1-2 mm)	135	15	Room temp	-	Immersion	-	Nitrogen release: * In water: -Uncoated urea: 100% of N in 1h. -L/MMT-coated urea: 34.6% of N in 105h. *In soil: -Uncoated urea: 100% in 30 days. -L/MMT-coated urea: 61.6% of N in 30 days.
[157]	Cellulose-g-poly(acrylamide)	Urea	Dissolved in water	80	-	80	300	Copolymerization	-	Nitrogen release: *In water: - CMC-g-PAM: 96% in 83 days. - CMC-g-PAM/ MMT (2.7, 5, 10 and 14.4 wt% MMT): 86.3, 78.8, 74.28 and 70.2% in 83 days, respectively.
	Cellulose-g-poly(acrylamide)/ Montmorillonite									
[158]	Dolomite-Alginate (DA)	KH <sub>2</sub> PO <sub>4</sub>	P-loaded DA beads	-	3h	100	-	Injected dropwise (CaCl <sub>2</sub> atomization)	-	Phosphorus release: * In water: - DA-coated KH <sub>2</sub> PO <sub>4</sub> : 40% in 10 days and about 90% in 60 days.
[112]	Alginate-g-poly (acrylic acid-co-acrylamide)/ Biochar	NPK	Loaded in the graft copolymers	80	-	50	Overnight	Graft copolymerization	-	N, P and K release: * In water: - Coated-NPK: 35% of N, 60% of P and 62% of K in 10 days.

										* In soil: -Coated-NPK: 60% of N, 30% of P and 30% of K in 30 days.
[159]	Sodium alginate-g-poly (acrylic acid-co-2-hydroxyethyl methacrylate)/ Montmorillonite	Urea	Dissolved in water	-	24	60	-	Loaded onto Alg-g-P(AA-co-HEMA)/MMT in aqueous solution	-	* In water: - Alg-g-P(AA-co-HEMA)/MMT (5%)-coated urea: 30% in 80 days. - Alg-g-P(AA-co-HEMA)/MMT (10%)-coated urea: 50% in 80 days.
[160]	Chitosan/alginate composites Gelatin/alginate composites	Urea	Dissolved in composite solution	-	2	Air flow	-	Urea-entrapped beads	-	Nitrogen release: * In water: - Chitosan/alginate-coated urea: 10% in 3h and 14% in 5h. - Chitosan/gelatin-coated urea: 6% in 3h and 8% in 5h.
[161]	Poly( $\epsilon$ -caprolactone)-g-Guar Gum and	DAP	4	-	-	30	-	Immersion	0.025	Nitrogen and phosphorus release: * In water: - Uncoated DAP: 100% in 1.5h -PCL-g-GG (1%) coated DAP: 100% of N in 45h and 100% of P in 35h -PCL-g-HNT (1%) coated DAP: 100% of N in 50h and 100% of P in 52h
	Poly( $\epsilon$ -caprolactone)-g-Hall oysite Nanotubes									
[47]	Polyvinyl Alcohol/Polylactic Acid core/shell fibers (PVA/PLA)	NPK	Dissolved in composite solution	90	-	-	-	Co-axial electrospinning	-	* In water: -NPK-loaded PVA/PLA core/shell fibers: 60% in 3 days, 80% in 28 days and 90% in 90 days. -NPK-loaded PVA fibers: 60% in 10 days and 70% in 20 days.
[162]	Polylactic acid/Cellulose acetate PLA/CA	Urea	~5	-	40	50	60	Immersion (phase inversion)	0.1-0.2	* In water: -PLA/CA-coated urea: 50% in 150 days and 100% in 650 days.
	Polylactic acid/Cellulose acetate/ nano-SiO <sub>2</sub> PLA/CA/SiO <sub>2</sub>									-PLA/CA/SiO <sub>2</sub> and PLA/CA/PEG-coated urea: 50% in 50 days and 100% in 150 days.
	Polylactic acid/Cellulose acetate/ Polyethylene glycol PLA/CA/PEG									

[163]	Hydroxymethylated lignin/Phenol-formaldehyde/ Talc (HML/PF/T)	Superphosphate	-	120	-	-	-	Rotating pan	-	Phosphorus release: * In water: -Uncoated superphosphate: 70% in 3 days. - HML/PF/T-coated superphosphate: 15% in 3 days.
[164]	Carboxymethyl cellulose/ $\beta$ -cyclodextrin-based microspheres (CMC/ $\beta$ -CD)	Urea	-	40	360	-	-	Graft copolymerization	-	Nitrogen release: * In water: -Uncoated urea: 100% in 24h. - CMC/ $\beta$ -CD -coated urea: 21.24% in 24h and 95.75% in 1 week.
[165]	k-Carrageenan/Glycerol	NPK	-	-	-	-	-	Immersion	-	* In water: -k-Carrageenan/Glycerol-coated NPK: 17% of $\text{NH}_4^+$ in 1h and 95% in 28 days, 23% of $\text{NO}_3^-$ in 24h and 68% in 28 days, 1.8% of $\text{PO}_4^{3-}$ in 10 mon and 62% in 28 days.
[108]	k-Carrageenan/Sodium Alginate/ Carboxymethyl Cellulose Hydrogel Blends NaAlg/KC/CMC	NPK	Dissolved in blend solution	-	-	-	-	Hydrogels through ionic crosslinking	-	* In soil: - NaAlg/KC/CMC-coated NPK: 53% in 3 days.
[166]	Bio-based amino-oil (Priamine)	DAP	2-4	-	-	60	-	Rotating pan	0.065 (single layer) 0.085 (double layer)	Phosphorus release: * In water: -Uncoated DAP: 100% of P in 2h. -Priamine-coated DAP: 100% of P in 98h (single layer) and 100% in 126h (double layer).

## **4. Effects of CRF@BB on soil & plant**

Over the last decades, various polymers have been widely used and have been found very promising for agricultural application. Most work involving polymers coated fertilizers focuses on the rate of nutrient release to water or soil (Table 2). However, papers investigated the combination effect of polymer/biopolymers and fertilizers (CRFs@BB) on soil properties and plant growth are scarce, and the work existing does not give details of the formulations and the polymers used. In this part, these works will be synthesized and the effect on some soil properties as well as on plant will be presented.

### **4.1. Effect of CRF@BB on soil properties**

#### **4.1.1. Effect of CRF@BB on the soil pH**

The soil pH is an important parameter for plant growth because it affects the availability of nutrient. Most nutrients are available to the plant roots in a soil pH of 5.5–7. Wang et al. [149] prepared a biomass-based CRF comprising urea granules, co-granulated with natural attapulgite and ammonium zinc phosphate as a fertilizer core, cellulose acetate butyrate as an inner coating, and carboxymethyl chitosan-g-poly(acrylic acid)/attapulgite hydrogel as an outer coating. The developed superabsorbent served as outer coating was immersed in a soil solution with pH values from 4 to 10 (adjusted with HCl or NaOH aqueous solution). Results showed that the superabsorbent-based biopolymers not only absorbed water to enhance plants survival in arid conditions, but also buffered the soil acidity or alkalinity to a pH of approximately 7. This is because of the large amounts of  $-\text{COOH}$  and  $-\text{COO}^-$  that can react with the  $\text{OH}^-$  and  $\text{H}^+$ , respectively, of soil solution. Another similar work was carried out by Boli et al. [167] using co-granulated beads based on urea, monopotassium phosphate and natural attapulgite clay as a core, guar gum as an inner coating, and guar gum-g-poly itaconic acid-co-acrylamide/humic acid superabsorbent polymer as an outer coating. Investigations showed that the superabsorbent buffered the soil solution to a pH of 7.09–7.3 from initial pH values that varied from 4 to 10.

#### **4.1.2. Effect of CRF@BB on the soil microbial biomass**

Soil microorganisms mediate many important biological processes for sustainable agriculture. They contribute in nutrient cycling, the degradation of agrochemicals and pollutants, etc. Soil microorganisms depend on soil organic C for energy and cell synthesis. The addition of

carbon-rich polymers can stimulate microorganisms. There have been few studies to date using biopolymers/polymers as coatings, and all of them involved polymer-coated N fertilizers without revealing the nature of the polymer that was used. This is probably because they use commercial coated fertilizers with confidential formulations. Zhang et al. [168] showed that a polymer-coated controlled-release urea increased the microbial biomass C and the functional diversity of bacteria more than urea at the majority of the study sites. This probably means that the nitrogen as well as the C contained in the coated urea was assimilated by the microorganisms. The microbial metabolic quotient  $qCO_2$  was higher for the control treatment (without fertilizer), because soil microorganisms were probably nutritionally stressed. Another work carried out by Nardi et al. [169] reported the effect of a polymer-coated urea on soil microbial biomass. They observed a higher microbial biomass C content in soil treated with CRFs than untreated soil. However, the soil microbial biomass N content with slow-release urea fertilizers was lower during the seedling stage than control treatment, but was higher after seedling stage. Inubushi et al. [170] also reported that the soil microbial biomass N was higher with conventional urea fertilizer than polymer-coated fertilizer. As to Chu et al. [171], they reported that controlled release urea did not significantly affect the microbial biomass, but had significant effects on soil microbial activities (dehydrogenase activity). This result is in accordance with the findings of Acquaye et al. [172] who reported that thermoplastic polyolefin-coated urea did not affect the amount of microbial biomass N.

#### **4.1.3. Effect of CRF@BB on nutrients bioavailability**

The coating serves as a protective layer to make soil-fertilizer contact difficult and limit interactions between the soil and the nutrients (e.g. phosphorus fixation). The nutrient availability can be governed by the nutrient release. There have only been a few studies to date that investigated the effect of CRF@BB on the availability of nutrients in soil. Garcia et al. [173] reported that lignin-coated TSP and rosin-coated DAP increased the P availability in calcareous soils and reduced P fixation. Diez et al. [174] also reported that rosin-coated DAPs provide control of P fixation in calcareous soils and that the P remains available for long periods. McKenzie et al. [175] reported that there was no difference between coated urea and uncoated urea in terms of N uptake, while Inubushi et al. [170] observed that coated fertilizer induced more N uptake by rice plants and a higher N fertilizer recovery rate than conventional fertilizer. Zhang et al. [176] reported that controlled-release urea reduced the potential N loss compared to urea.

Cruz et al. [177] studied the effect of polyurethane-coated DAP fertilizer on P availability in an oxisol. They argued that the thickness of the coating affects P availability. According to the same authors, non-coated or DAP with a thin coat decreased the P availability due to high P adsorption by the soil colloids, while DAP with a thicker coat increased the available P due to its slow release and the shorter contact time of P with the soil.

Castro et al. [178] compared the migration of P in soil at 63% WHC through uncoated MAP and polymer-coated MAP in an oxisol (pH between 5.2 and 7). The distribution pattern of P with the two treatments was not significantly different. The majority of the P from MAP and the coated MAP (> 80%) remained within 0–7.5 mm from the point of application and the remaining P did not migrate beyond a 25.5 mm radius of the fertilizer granule. Lombi et al. [179] and Lawton et al. [180] found the same diffusion radius for P using different P sources (MAP, DAP, TSP, and others) in different water-saturated soils (calcareous, oxisol, and loamy soils).

#### **4.1.4. Effect of CRF@BB on the water holding capacity and water retention**

Several researches are carried out to evaluate the biopolymers effect on soil physical properties. In this sense, Montesano et al. [181] studied the effect of cellulose-based superabsorbent hydrogels on the water retention properties of the soil. They showed that cellulose dramatically improve water retention and water holding capacity of a sandy soil and perlite (soilless substrate). Similar results have been reported by Tran et al. [182] who suggested that the addition of biopolymers (starch and xanthan gum hydrogels) significantly improve the water holding capacity in sandy soils. This highest amount of water retained can be explained by hydrophilic groups and network structure in biopolymer and by the formation of strong hydrogen bonding between water molecules and these biopolymers. Soils treated with biopolymer-coated fertilizers and/or superabsorbent-coated fertilizers also enhance the water retention and water holding capacity of the soil. The water-holding capacity and the water retention of soils with coated fertilizers always exceed those of soils with uncoated fertilizers. Table 3 summarizes the results of some of the studies to date.

<b>Table 3</b>				
Comparison between the water-holding capacity (WHC) and the water retention (WR) of soil in the presence/absence of coating				
	WHC (%)		WR (wt%) (1-Water evaporation (wt%))	
	Without Coating	With Coating	Without Coating	With Coating
[183]	28.2	40.8	7% after 10 days 0% after 20 days	23.7% after 10 days 14% after 20 days
[184]	41.5	54	0 after 4 weeks	30.8% after 2 weeks
[185]	28.17	40.26	10.4% after 10 days 2.1% after 20 days 0% after 30 days	25.1% after 10 days 13.2% after 20 days 3.9% after 30 days
[5]	30.17	40.35	12.4% after 10 days 2.6% after 20 days 0% after 30 days	24.7% after 10 days 15.5% after 20 days 7.8% after 30 days
[148]	-	59	- 0% after 10 days	113.5% after 0 days 62% after 10 days
[145]	29.08	39.76	44% after 15 days 5.5% after 30 days	56.5% after 15 days 22% after 30 days
[149]	38.5	69	5.1% after 15 days 0% after 18 days	49.8% after 15 days 44.1% after 18 days
[150]	29.35	41.8	49% after 12 days 5% after 21 days	64.5% after 12 days 27% after 21 days
[186]	33.1	46.8	41% after 15 days 6.5% after 30 days	65.6% after 15 days 24.8% after 30 days

#### 4.2. Effect of CRF@BB on plant growth

Over their undeniable role in controlled nutrient release and soil stabilization, biopolymers can offer positive long-term effects on vegetation growth. Many studies have found a positive relationship between biopolymers and plant growth. In this regard, Niekraszewicz et al. [187] investigated the effect of different biopolymer compositions on the stimulation of plant growth. The authors were able to show that biopolymers-based formulations (chitosan and hemicellulose) have an antiviral action. This action reflects two phenomena: (1) blocking of virus-specific receptors as a result of the affinity of the polymers for these receptors (2) induction of the immune system against pathogens. They showed that the various formulations had a markedly positive impact as growth regulators of germination (accelerating seed germination), growth, and health of the seedlings. In the same context,

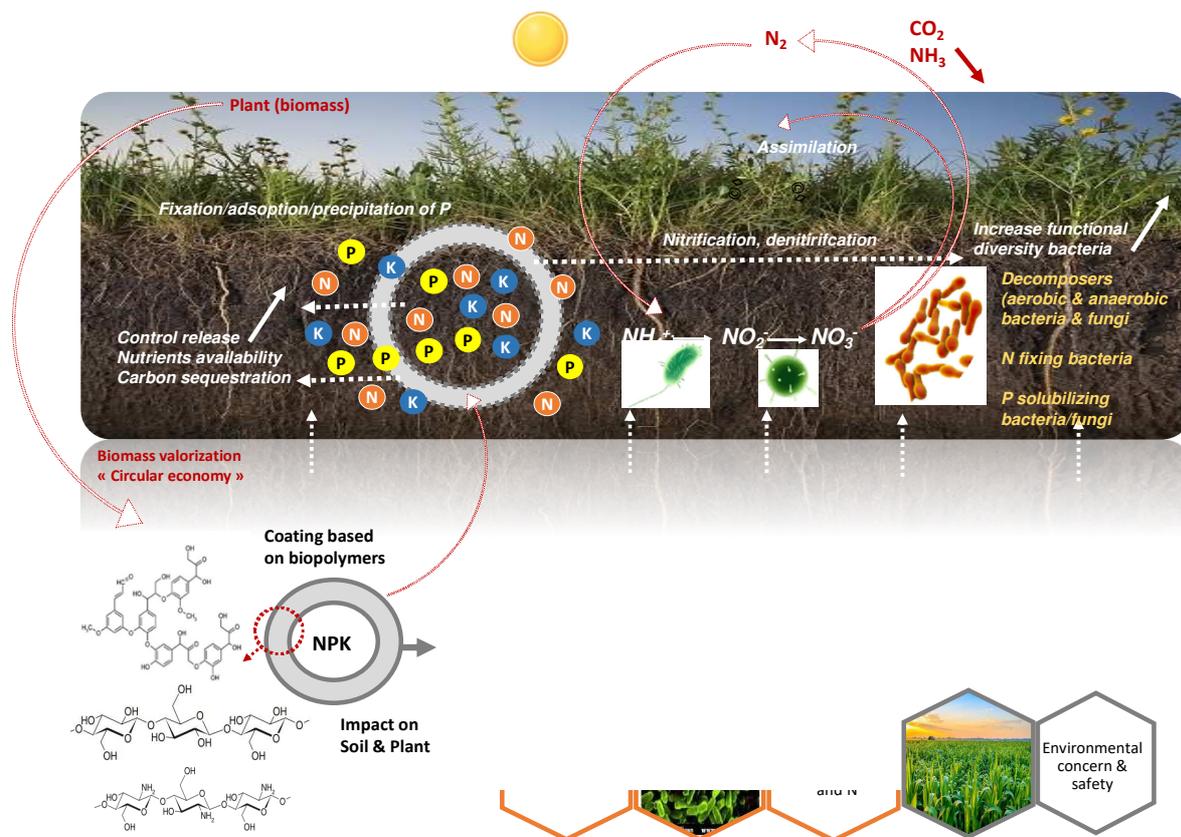
Kumaraswamy et al. [188] reported that nanocomposites based on chitosan can either be used as biostimulants or biopesticides to fight against diseases and to promote growth. On the other hand, Shamshina et al. [189] reported that adding chitin and its derivatives to the soil promotes the activities of many beneficial microorganisms (chitinolytic microbes), which act as a biological control against many agents responsible for plant infections and diseases. In this regard, Sharp [190] reported that the efficiency of a treatment based on chitin was comparable to those obtained with currently available synthetic pesticides and fertilizers. According to Sharp, this behavior can be explained by the fact that chitin and its derivatives are toxic to pests and plant pathogens as they induce plant defenses and they simulate the activity of beneficial microbes. Similar results have been observed for biodegradable hydrogels based on cellulose, with significantly enhanced plant growth and limitation of the effects of water stress [181]. The effect of vegetal biopolymer as a biostimulant on root growth and resistance to plant stress was recently investigated [191]. The findings of this study demonstrated that vegetal biopolymer-based biostimulants promoted plant growth and significantly protected plants from both abiotic and biotic stress factors.

Few papers to date have investigated the effect of the combination of CRF@BBs on plant growth. Qian et al. [192] compared the effect of conventional MAP granules and CFRs based on polymer-coated MAP granules on wheat, canola, mustard, flax, yellow pea, and alfalfa. Field experiments were conducted in a P-deficient brown soil from Canada. The results showed that the CFRs increased the tolerance of crops to high levels of P placed in seed rows, with levels of 80 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> placed in the seed rows. This effect could be explained by the fact that CFRs reduced the salt effect of high levels of fertilizer in close proximity to the seed. Tian et al. [193] investigated the effect of a coated NPK fertilizer without providing details about the nature of the coating. Field experiments were conducted for early ripening rapeseed in the red-yellow soil of southern China. The same amount of non-coated fertilizer (control) and coated fertilizer (CRFs) was applied. The comparison of plant height, first branch numbers, pod numbers, stem dry weight, and pod dry weight between the two treatments revealed that the use of a CRF resulted in a 14.5% higher seed yield than the control. Landis et al. [194] compared polymer-encapsulated sulfur-coated urea to standard fertilizer. The tests were performed on red pine, jack pine, white spruce, and other conifers. The results showed that the seedlings were larger, with fewer culls, when CRFs were used. McKenzie et al. [175] reported that there was no difference between polymer-coated urea and non-coated urea in terms of the grain yield and the grain protein concentration when fertilizers were side-banded

in the fall, whereas the use of CRU was highly effective for reducing seedling damage caused by seed row application of urea. A similar finding has also been reported by Middleton et al. [195], who argued that CRU did not injure seedlings even when applied in large quantities. Zhang et al. [176] reported that polymer-controlled-release urea had no effect on the barley grain yield although it did increase its protein content compared to urea.

## 5. Challenges and perspectives

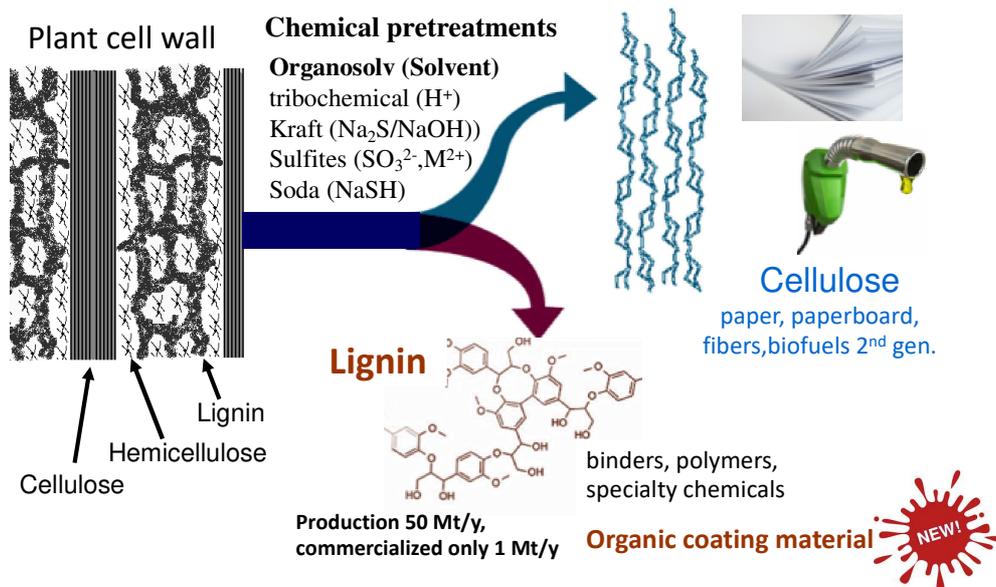
CRFs show substantial potential in improving nutrients control release and reducing the environmental impact in comparison to traditional minerals fertilizer. Inorganic and/or organic coating materials can be used as diffusion barriers to produce CRF and to control the NPK release rate. However, because of their non-biodegradable and non-renewable character and their potential environmental risks, fossil-based polymers are far from being green and an ideal candidate for coating fertilizers, which limits their commercial application. Hence, biopolymers-based composites and nanocomposites have great potential to be used in environmentally friendly applications such as coating materials for mineral fertilizers.



**Fig.6.** Future perspectives of biopolymers in agricultural application

In response to a strong marketing trend toward more environmentally friendly, organic coating materials based on biopolymers have some advantages and certain important specifications compared to synthetic polymers, which summarized in Fig.6, hydrophilicity and production cost are the most challenges faced by biopolymer-coated fertilizers, and the major limitation that needs to be overcome in order to allow such replacement.

- **Hydrophilicity:** The majority of biopolymers are hydrophilic. To enhance their application in CRFs, several attempts have been investigated to address this challenge and to improve their hydrophobicity by making some chemical modification (i.e. functionalization of molecules [196]). Another option is by adding mineral clay (montmorillonite, kaolin, etc.) [2] or by combining them with other synthetic polymers (polyacrylamide, polyvinyl alcohol, etc.) [197,198].
- **Cost of biopolymers production:** Another several challenge that needs to be overcome to accelerate the commercialization of the final product, is the cost of biopolymer production. The cost depends strongly on the type of biopolymer and production process. In general, biopolymers used for fertilizers coating are extracted from biomass, according to several stages: i) extraction using either a solvent or a chemical catalyst; ii) filtration and washing, iii) purification; iv) drying and lyophilization [94,96]. However, all these additional steps increase the cost of the final biopolymer production, with an additional expense related to adding materials coating on a fertilizer particle (materials coating is expensive compared to uncoated materials as well as the manufacturing process) limit their use on a large scale. Another very important parameter is the availability of biomass (algal, wood, etc.) and the competition or not with other sectors (food/feed, cosmetic). Ideally, in the future, it must be focused on biopolymers, which are not in competition to another fields and their extraction methods do not require high investment cost and do not consume a high quantity of chemical products and high energy, or using waste or co-product biopolymers produced from different biorefinery (Fig.7) (paper industry, oil extraction, sugars fermentation cosmetic extraction).



**Fig.7.** Biorefinery scheme of lignin production as a new organic coating material

There are other several challenges that need to be overcome to accelerate the commercialization of the final product. The relatively constant rate of nutrient elements release under stable temperatures can damage the plant or may not provide the right amount of nutrients at the right time. In fact, plants require different amounts of nutrients depending on their growing stage. When the plant is young, it requires less nutrients than the maturation stage. In addition, the biopolymers used as coating materials are susceptible to biodegradation under particular soil conditions and microorganisms of the ecosystem (susceptible to microbial-enzyme attack), which does not allow the nutrients to be released over an extended period leading.

Another challenge is the use of superabsorbent polymer hydrogels based on biopolymeric materials in improving soil conditions as an environmentally friendly alternative to alkyl acrylate or alkyl methacrylate polymers frequently used as a soil conditioner. To improve the swelling capacity of these biopolymers, to diminish the environmental concerns and waste accumulation caused by non-biodegradable materials and to expand the opportunity to enhance their application in agriculture, several attempts have been investigated. One option is making composites either by adding mineral nanofillers (nanoclay) or by developing composite hydrogels and in terms of structure and architecture of polymer, by making biodegradable amphiphilic block copolymers; because they have the ability to self-associate to form structures of nanometric sizes and varied morphologies. Although the necessity to combine the swelling capacity or water retention with controlled release properties of coating

materials still remains a challenge, but the new research strategies based on the principles of green chemistry and the use of biodegradable polymers as new materials with an excellent ability to manage nutrient release profiles; can lead to new discoveries in this field and make these polymers as promoting materials for improved agricultural management.

In view of above mentioned previous studies and challenges, biopolymers are proving to be an ideal candidate to replacing polymers derived from petroleum resources for CRF production. In order to continue to benefit from their particular properties and potential responding to environmental concerns, it would therefore be necessary to develop new organic coating based on biopolymers, more reliable, renewable, not competitive with another industry, less expensive and non-polluting chemical modifications. Due to its functional properties, low cost, and wide sources, lignin has a good potential for preparing controlled-release fertilizers [199]. Lignin (Fig.7) is a phenolic polymer, and one of the main components of lignocellulosic biomass, makes up 15% to 40% of dry matter of woody and gramineous plants. The worldwide production of lignin is estimated to 100 million tonnes/year equivalent to USD 732.7 million in 2015 with only 1-2Mt/year are valorized [200]. Different categories of lignin are produced (ligno-sulphonate, kraft lignins, organosolv) according to classical processes (Kraft process, Sulphite process, Soda process, etc.) that are largely used in the paper industry. Lignin serves also as a cheaper and biodegradable chelating agent to decrease the leaching of iron and zinc [201]. At the same time, lignin, as a urease inhibitor, can reduce the nitrification rate of urea and enable urea to remain in the soil longer [202]. Lignin reduces significantly the release rate of nutrients fertilizer [116,133]. However, lignin presents some disadvantage, for example it is soluble only in alkaline medium, very heterogeneous and with low water retention properties and cannot form a homogeneous film, which decrease its adhesion to NPK surface compared to alginate and chitosan for example. To improve coating properties, lignin also has been modified by physical and chemical methods, for example, steam explosion [203], ammoxidation [204], Mannich reaction [205], phenolation [206], and hydroxymethylation [207]. The mixture of lignin polymer with different organic and inorganic materials (clay, SiO<sub>2</sub>, chitosan, nanocelluloses) could improve its cross-link reactivity and to increase its adhesion to mineral fertilizers (NPK). Another strategy is the fabrication of biomimetic superhydrophobic films based on lignin and/or other biopolymers lignocellulosic inspired by plant cell wall and the micronanoscale structural properties of natural superhydrophobic surfaces, such as self-healing, self-cleaning and water/oil separation.

## **6. Conclusion**

Synchronizing nutrient release rate of coated fertilizers with the nutrient demand of plants according to their growth period is one of the most effective and promoting strategy to improve the use efficiency of nutrients and reduce environmental pollution caused by conventional fertilizers. Comprehensive efforts are also being made to strategies that are more efficient to achieve these objectives. Today, biopolymers appear as environmentally green and indispensable materials for replacing oil-based polymers to encapsulate agrochemicals compounds and for various agricultural applications in order to overcome the undesirable environmental impacts and potential contamination ecosystems. These materials should not only fulfil the demands of the market including environmentally, technically, socially and economically sustainable, but also goes a long way toward satisfying future requirements to produce smart polymers with biodegradable and renewable properties in nanotechnology concept. In addition, study the different environmental conditions that may influence these biofertilizers based on biopolymers efficiency, such as temperature, soil type, moisture, etc.

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## References

- [1] B. Azeem, K. Kushaari, Z.B. Man, A. Basit, T.H. Thanh, Review on materials & methods to produce controlled release coated urea fertilizer, *J. Control. Release.* 181 (2014) 11–21. doi:10.1016/j.jconrel.2014.02.020.
- [2] B.R. Dos Santos, F.B. Bacalhau, T.D.S. Pereira, C.F. Souza, R. Faez, Chitosan-montmorillonite microspheres: A sustainable fertilizer delivery system, *Carbohydr. Polym.* 127 (2015) 340–346. doi:10.1016/j.carbpol.2015.03.064.
- [3] FAO, World fertilizer trends and outlook to 2020, Food Agric. Organ. United Nations. (2017) 1–38.
- [4] A. Rashidzadeh, A. Olad, Slow-released NPK fertilizer encapsulated by NaAlg-g-poly(AA-co-AAm)/MMT superabsorbent nanocomposite, *Carbohydr. Polym.* 114 (2014) 269–278. doi:10.1016/j.carbpol.2014.08.010.
- [5] L. Wu, M. Liu, Preparation and properties of chitosan-coated NPK compound fertilizer with controlled-release and water-retention, *Carbohydr. Polym.* 72 (2008) 240–247. doi:10.1016/j.carbpol.2007.08.020.
- [6] M.N. Khan, M. Mobin, Z.K. Abbas, S.A. Alamri, Fertilizers and Their Contaminants in Soils, Surface and Groundwater, *Encycl. Anthr.* (2017) 225–240. doi:10.1016/b978-0-12-809665-9.09888-8.
- [7] Y.P. Timilsena, R. Adhikari, P. Casey, T. Muster, H. Gill, B. Adhikari, Enhanced efficiency fertilisers: A review of formulation and nutrient release patterns, *J. Sci. Food Agric.* 95 (2015) 1131–1142. doi:10.1002/jsfa.6812.
- [8] P. Rychter, M. Kot, K. Bajer, D. Rogacz, A. Šišková, J. Kapušniak, Utilization of starch films plasticized with urea as fertilizer for improvement of plant growth, *Carbohydr. Polym.* 137 (2016) 127–138. doi:10.1016/j.carbpol.2015.10.051.
- [9] D. Ronga, F. Caradonia, M. Parisi, G. Bezzi, B. Parisi, G. Allesina, S. Pedrazzi, E. Francia, Using digestate and biochar as fertilizers to improve processing tomato production sustainability, *Agronomy.* 10 (2020) 1–14. doi:10.3390/agronomy10010138.
- [10] L. Verdi, P.J. Kuikman, S. Orlandini, M. Mancini, M. Napoli, A. Dalla Marta, Does the use of digestate to replace mineral fertilizers have less emissions of N<sub>2</sub>O and NH<sub>3</sub>? , *Agric. For. Meteorol.* 269–270 (2019) 112–118. doi:10.1016/j.agrformet.2019.02.004.
- [11] M. Radziemska, M.D. Vaverková, D. Adamcová, M. Brtnický, Z. Mazur, Valorization of Fish Waste Compost as a Fertilizer for Agricultural Use, *Waste and Biomass Valorization.* 10

- (2019) 2537–2545. doi:10.1007/s12649-018-0288-8.
- [12] J.L. Liang, J. Liu, P. Jia, T. tao Yang, Q. wei Zeng, S. chang Zhang, B. Liao, W. sheng Shu, J. tian Li, Novel phosphate-solubilizing bacteria enhance soil phosphorus cycling following ecological restoration of land degraded by mining, *ISME J.* 14 (2020) 1600–1613. doi:10.1038/s41396-020-0632-4.
- [13] W. Wan, Y. Qin, H. Wu, W. Zuo, H. He, J. Tan, Y. Wang, D. He, Isolation and Characterization of Phosphorus Solubilizing Bacteria With Multiple Phosphorus Sources Utilizing Capability and Their Potential for Lead Immobilization in Soil, *Front. Microbiol.* 11 (2020) 1–15. doi:10.3389/fmicb.2020.00752.
- [14] M. Billah, M. Khan, A. Bano, T.U. Hassan, A. Munir, A.R. Gurmani, Phosphorus and phosphate solubilizing bacteria: Keys for sustainable agriculture, *Geomicrobiol. J.* 36 (2019) 904–916. doi:10.1080/01490451.2019.1654043.
- [15] M. Seif Sahandi, A. Mehrafarin, H. Naghdi Badi, F. Khalighi-Sigaroodi, M. Sharifi, Improving growth, phytochemical, and antioxidant characteristics of peppermint by phosphate-solubilizing bacteria along with reducing phosphorus fertilizer use, *Ind. Crops Prod.* 141 (2019) 111777. doi:10.1016/j.indcrop.2019.111777.
- [16] D.W. Rindt, G.M. Blouin, J.G. Getsinger, Sulfur coating on nitrogen fertilizer to reduce dissolution rate, *J. Agric. Food Chem.* 16 (1968) 773–778. doi:10.1021/jf60159a015.
- [17] G.M. Blouin, D.W. Rindt, O.E. Moore, Sulfur-coated fertilizers for controlled release: Pilot plant production, *J. Agric. Food Chem.* 19 (1971) 801–808. doi:10.1021/jf60177a039.
- [18] M. Devassine, F. Henry, P. Guerin, X. Briand, Coating of fertilizers by degradable polymers, *Int. J. Pharm.* 242 (2002) 399–404. doi:10.1016/S0378-5173(02)00225-9.
- [19] A. Jarosiewicz, M. Tomaszewska, Controlled-Release NPK Fertilizer Encapsulated by Polymeric, *J. Agric. Food Chem.* 51 (2003) 413–417. doi:10.1021/jf020800o.
- [20] M.M.E. Costa, E.C.M. Cabral-Albuquerque, T.L.M. Alves, J.C. Pinto, R.L. Fialho, Use of polyhydroxybutyrate and ethyl cellulose for coating of urea granules, *J. Agric. Food Chem.* 61 (2013) 9984–9991. doi:10.1021/jf401185y.
- [21] M.E. Trenkel, Controlled-Release and Stabilized Fertilizers in Agriculture, *Int. Fertil. Ind. Assoc.* (1997) 1–151.
- [22] B. Azeem, K. KuShaari, M. Naqvi, L.K. Keong, M.K. Almesfer, Z. Al-Qodah, S.R. Naqvi, N. Elboughdiri, Production and characterization of controlled release urea using biopolymer and geopolymer as coating materials, *Polymers (Basel).* 12 (2020) 1–30.

doi:10.3390/polym12020400.

- [23] B. Tomadoni, C. Casalongué, V.A. Alvarez, *Polymers for Agri-Food Applications*, *Polym. Agri-Food Appl.* (2019) 109–125. doi:10.1007/978-3-030-19416-1.
- [24] J.J. Perez Bravo, N.J. François, *Chitosan/Starch Matrices Prepared by Ionotropic Gelation: Rheological Characterization, Swelling Behavior and Potassium Nitrate Release Kinetics*, *J. Polym. Environ.* 28 (2020) 2681–2690. doi:10.1007/s10924-020-01798-5.
- [25] B.C. Cerri, L.M. Borelli, I.M. Stelutti, M.R. Soares, M.A. da Silva, *Evaluation of new environmental friendly particulate soil fertilizers based on agroindustry wastes biopolymers and sugarcane vinasse*, *Waste Manag.* 108 (2020) 144–153. doi:10.1016/j.wasman.2020.04.038.
- [26] M.E. Trenkel, *Slow and Controlled-Release and stabilized Fertilizers*, *Int. Fertil. Ind. Assoc.* (2010) 1–163. doi:10.1017/CBO9781107415324.004.
- [27] A. Shaviv, *Controlled Release Fertilizers*, *IFA Int. Work. Enhanc. Fertil.* (2005) 1–13.
- [28] L. Xie, M. Liu, B. Ni, Y. Wang, *New environment-friendly use of wheat straw in slow-release fertilizer formulations with the function of superabsorbent*, *Ind. Eng. Chem. Res.* 51 (2012) 3855–3862. doi:10.1021/ie2016043.
- [29] B. Ni, M. Liu, S. Luü, L. Xie, X. Zhang, Y. Wang, *Novel slow-release multielement compound fertilizer with hydroscopicity and moisture preservation*, *Ind. Eng. Chem. Res.* 49 (2010) 4546–4552. doi:10.1021/ie9019769.
- [30] H. Dittmar, M. Drach, R. Vosskamp, M.E. Trenkel, R. Gutser, G. Steffens, *Fertilizers, 2. types*, *Ullmann's Encycl. Ind. Chem.* (2009) 200–246. doi:10.1002/14356007.n10.
- [31] J.J. Oertli, O.R. Lunt, *Controlled Release of Fertilizer Minerals by Incapsulating Membranes: I. Factors Influencing the Rate of Release*, *Soil Sci. Soc. Am. J.* 26 (1962) 579–583. doi:10.2136/sssaj1962.03615995002600060019x.
- [32] M.L. Heilig, *Process for preparing slow release fertilizer composition*, *United States Pat. Off.* (1963) 1–6. doi:10.1145/178951.178972.
- [33] H. Óskarsson, A. Sigurgeirsson, K. Raulund-Rasmussen, *Survival, growth, and nutrition of tree seedlings fertilized at planting on Andisol soils in Iceland: Six-year results*, *For. Ecol. Manage.* 229 (2006) 88–97. doi:10.1016/j.foreco.2006.03.018.
- [34] D. White, *Survival, growth, and nutrient uptake by Spruce and Pine seedlings as affected by slow-release fertilizer materials*, *For. Relationships North Am.* (1965) 47–63.

- [35] L.I. Hansen, Slow release fertilizer granule having a plurality of urethane resin coatings, United States Pat. Off. (1966) 1–6. doi:10.1145/178951.178972.
- [36] D.F. Jacobs, Variation in nutrient release of polymer-coated fertilizers, *Natl. Proc. For. Conserv. Nurs. Assoc.* 2004. 35 (2004) 113–118.
- [37] F.H. Otey, D. Trimmell, R.P. Westhoff, B.S. Shasha, Starch Matrix for Controlled Release of Urea Fertilizer Felix, *J. Agric. Food Chem.* 32 (1984) 1095–1098. doi:10.1021/jf00125a041.
- [38] M.A. Teixeira, W.J. Paterson, E.J. Dunn, Q. Li, B.K. Hunter, M.F.A. Goosen, B.K. Hunter, Assessment of Chitosan Gels for the Controlled Release of Agrochemicals, *Ind. Eng. Chem. Res.* 29 (1990) 1205–1209. doi:10.1021/ie00103a019.
- [39] M. García, J.A. Díez, A. Vallejo, L. García, M.C. Cartagena, Use of Kraft Pine Lignin in Controlled-Release Fertilizer, *Ind. Eng. Chem. Res.* 35 (1996) 245–249. doi:10.1021/ie950056f.
- [40] IHS Markit, *Chem. Econ. Handb.* (2018) <https://ihsmarkit.com/>.
- [41] G. Liu, L. Zotarelli, Y. Li, D. Dinkins, Q. Wang, M. Ozores-Hampton, Controlled-Release and Slow-Release Fertilizers as Nutrient Management Tools, *IFAS Ext.* (2017) 1–6.
- [42] V.R. Remya, S.J. George, T. Sabu, Polymer formulations for controlled release of fertilizers, *Acad. Press.* (2021) 183–194.
- [43] K. Rop, G.N. Karuku, D. Mbui, I. Michira, N. Njomo, Formulation of slow release NPK fertilizer (cellulose-graft-poly(acrylamide)/nano-hydroxyapatite/soluble fertilizer) composite and evaluating its N mineralization potential, *Ann. Agric. Sci.* 63 (2018) 163–172. doi:10.1016/j.aos.2018.11.001.
- [44] M.A. Schmidt, A.J. Kreinberg, J.M. Gonzalez, J.J. Halvorson, E. French, A. Bollmann, A.E. Hagerman, Soil microbial communities respond differently to three chemically defined polyphenols, *Plant Physiol. Biochem.* 72 (2013) 190–197. doi:10.1016/j.plaphy.2013.03.003.
- [45] P. Calcagnile, T. Sibillano, C. Giannini, A. Sannino, C. Demitri, Biodegradable poly(lactic acid)/cellulose-based superabsorbent hydrogel composite material as water and fertilizer reservoir in agricultural applications, *J. Appl. Polym. Sci.* 136 (2019) 1–9. doi:10.1002/app.47546.
- [46] S. Hakim, M.R.R. Darouk, Hanieh Talari, M. Barghemadi, M. Parvazinia, Fabrication of PVA/Nanoclay Hydrogel Nanocomposites and Their Microstructural Effect on the Release Behavior of a Potassium Phosphate Fertilizer, *J. Polym. Environ.* 27 (2019) 2925–2932. doi:10.1007/s10924-019-01580-2.

- [47] P. Nooeaid, P. Chuysinuan, W. Pitakdantham, D. Aryuwananon, S. Techasakul, D. Dechtrirat, Eco-Friendly Polyvinyl Alcohol/Poly(lactic Acid) Core/Shell Structured Fibers as Controlled-Release Fertilizers for Sustainable Agriculture, *J. Polym. Environ.* (2020). doi:10.1007/s10924-020-01902-9.
- [48] V.A.R. Baldanza, F.G. Souza, S.T. Filho, H.A. Franco, G.E. Oliveira, R.M.J. Caetano, J.A.R. Hernandez, S.G. Ferreira Leite, A.M. Furtado Sousa, A.L. Nazareth Silva, Controlled-release fertilizer based on poly(butylene succinate)/urea/clay and its effect on lettuce growth, *J. Appl. Polym. Sci.* 135 (2018) 51–60. doi:10.1002/app.46858.
- [49] T. Qi, S. Lü, T. Li, J. Chen, M. Huang, Y. Ji, S.F. Zhang, M. Liu, A multielement compound fertilizer used polydopamine and sodium carboxymethyl starch matrices as coatings, *Int. J. Biol. Macromol.* 124 (2019) 582–590. doi:10.1016/j.ijbiomac.2018.11.245.
- [50] X. Xiao, L. Yu, F. Xie, X. Bao, H. Liu, Z. Ji, L. Chen, One-step method to prepare starch-based superabsorbent polymer for slow release of fertilizer, *Chem. Eng. J.* 309 (2017) 607–616. doi:10.1016/j.cej.2016.10.101.
- [51] J. Chen, X. Fan, L. Zhang, X. Chen, S. Sun, R.C. Sun, Research Progress in Lignin-Based Slow/Controlled Release Fertilizer, *ChemSusChem*. 13 (2020) 4356–4366. doi:10.1002/cssc.202000455.
- [52] H. Gu, Y. Zhang, X. Li, W. Li, S. Huang, Lignin improves release behavior of slow-release fertilizers with high content of urea, *J. Appl. Polym. Sci.* 136 (2019) 1–8. doi:10.1002/app.48238.
- [53] A. Olad, H. Zebhi, D. Salari, A. Mirmohseni, A. Reyhani, Slow-release NPK fertilizer encapsulated by carboxymethyl cellulose-based nanocomposite with the function of water retention in soil, *Mater. Sci. Eng. C*. 90 (2018) 333–340. doi:10.1016/j.msec.2018.04.083.
- [54] S. Mohammadi-khoo, P.N. Moghadam, A.R. Fareghi, Synthesis of a cellulose-based hydrogel network : Characterization and study of urea fertilizer slow release, *J. Appl. Polym. Sci.* 42935 (2016) 1–9. doi:10.1002/app.42935.
- [55] D.J. Sarkar, T. Bera, A. Singh, Release of urea from cellulosic hydrogel coated urea granule : Modeling effect of crosslink density and pH triggering, *Polym. Technol. Mater.* 0 (2019) 1–13. doi:10.1080/25740881.2019.1587772.
- [56] T. Li, B. Gao, Z. Tong, Y. Yang, Y. Li, Chitosan and Graphene Oxide Nanocomposites as Coatings for Controlled-Release Fertilizer, *Water. Air. Soil Pollut.* 230 (2019) 1–19. doi:10.1007/s11270-019-4173-2.
- [57] D. França, Â.F. Medina, L.L. Messa, C.F. Souza, R. Faez, Chitosan spray-dried microcapsule

- and microsphere as fertilizer host for swellable – controlled release materials, *Carbohydr. Polym.* 196 (2018) 47–55. doi:10.1016/j.carbpol.2018.05.014.
- [58] M.D. Gumelar, M. Hamzah, A.S. Hidayat, D.A. Saputra, Idvan, Utilization of Chitosan as Coating Material in Making NPK Slow Release Fertilizer, *Macromol. Symp.* 391 (2020) 1–4. doi:10.1002/masy.201900188.
- [59] M.M. Iftime, G.L. Ailiesei, E. Ungureanu, L. Marin, Designing chitosan based eco-friendly multifunctional soil conditioner systems with urea controlled release and water retention, *Carbohydr. Polym.* 223 (2019) 115040. doi:10.1016/j.carbpol.2019.115040.
- [60] G.O. Akalin, M. Pulat, Preparation and characterization of  $\kappa$ -carrageenan hydrogel for controlled release of copper and manganese micronutrients, *Polym. Bull.* 77 (2020) 1359–1375. doi:10.1007/s00289-019-02800-4.
- [61] K.P. Chandrika, A. Singh, A. Rathore, A. Kumar, Novel cross linked guar gum-g-poly(acrylate) porous superabsorbent hydrogels: Characterization and swelling behaviour in different environments, *Carbohydr. Polym.* 149 (2016) 175–185. doi:10.1016/j.carbpol.2016.04.077.
- [62] Sukriti, B.S. Kaith, R. Jindal, Controlled biofertilizer release kinetics and moisture retention in gum xanthan-based IPN, *Iran. Polym. J.* 26 (2017) 563–577. doi:10.1007/s13726-017-0539-8.
- [63] C. Vudjung, S. Saengsuwan, Biodegradable IPN Hydrogels Based on Pre-vulcanized Natural Rubber and Cassava Starch as Coating Membrane for Environment-Friendly Slow-Release Urea Fertilizer, *J. Polym. Environ.* 26 (2018) 3967–3980. doi:10.1007/s10924-018-1274-8.
- [64] Y.C. Yang, M. Zhang, Y. Li, X.H. Fan, Y.Q. Geng, Improving the quality of polymer-coated urea with recycled plastic, proper additives, and large tablets, *J. Agric. Food Chem.* 60 (2012) 11229–11237. doi:10.1021/jf302813g.
- [65] E.M.N. Polman, G.J.M. Gruter, J.R. Parsons, A. Tietema, Comparison of the aerobic biodegradation of biopolymers and the corresponding bioplastics: A review, *Sci. Total Environ.* 753 (2021) 141953. doi:10.1016/j.scitotenv.2020.141953.
- [66] I. Chang, J. Im, G.C. Cho, Introduction of microbial biopolymers in soil treatment for future environmentally-friendly and sustainable geotechnical engineering, *Sustainability.* 8 (2016) 251. doi:10.3390/su8030251.
- [67] C. Zhou, P.S. So, X.W. Chen, A water retention model considering biopolymer-soil interactions, *J. Hydrol.* 586 (2020) 124874. doi:10.1016/j.jhydrol.2020.124874.
- [68] E.A. Reis, M.H.M. Rocha-Leão, S.G.F. Leite, Slow-release nutrient capsules for

- microorganism stimulation in oil remediation, *Appl. Biochem. Biotechnol.* 169 (2013) 1241–1249. doi:10.1007/s12010-012-0022-0.
- [69] Z. Majeed, N.K. Ramli, N. Mansor, Z. Man, A comprehensive review on biodegradable polymers and their blends used in controlled-release fertilizer processes, *Rev. Chem. Eng.* 31 (2015) 69–95. doi:10.1515/revce-2014-0021.
- [70] V.P. Santos, N.S.S. Marques, P.C.S.V. Maia, M.A.B. de Lima, L. de O. Franco, G.M. de Campos-Takaki, Seafood waste as attractive source of chitin and chitosan production and their applications, *Int. J. Mol. Sci.* 21 (2020) 1–17. doi:10.3390/ijms21124290.
- [71] G.K. Chatzoudis, F. Rigas, Macroreticular hydrogel effects on dissolution rate of controlled-release fertilizers, *J. Agric. Food Chem.* 46 (1998) 2830–2833. doi:10.1021/jf970969f.
- [72] Y. Shen, C. Zhao, J. Zhou, C. Du, Application of waterborne acrylic emulsions in coated controlled release fertilizer using reacted layer technology, *Chinese J. Chem. Eng.* 23 (2015) 309–314. doi:10.1016/j.cjche.2014.09.034.
- [73] Z. Cong, S. Yazhen, D. Changwen, Z. Jianmin, W. Huoyan, C. Xiaoqin, Evaluation of waterborne coating for controlled-release fertilizer using Wurster fluidized bed, *Ind. Eng. Chem. Res.* 49 (2010) 9644–9647. doi:10.1021/ie101239m.
- [74] S. Perez-Garcia, M. Fernandez-Perez, M. Villafranca-Sanchez, E. Gonzalez-Pradas Francisco, Flores-Céspedes, Controlled release of ammonium nitrate from ethylcellulose coated formulations, *Ind. Eng. Chem. Res.* 46 (2007) 3304–3311. doi:10.1021/ie061530s.
- [75] Y.H. Lum, A. Shaaban, N.M.M. Mitan, M.F. Dimin, N. Mohamad, N. Hamid, S.M. Se, Characterization of Urea Encapsulated by Biodegradable Starch-PVA-Glycerol, *J. Polym. Environ.* 21 (2013) 1083–1087. doi:10.1007/s10924-012-0552-0.
- [76] K. Lubkowski, Coating fertilizer granules with biodegradable materials for controlled fertilizer release, *Environ. Eng. Manag. J.* 13 (2014) 2573–2581. doi:10.30638/eemj.2014.287.
- [77] S. Lü, C. Gao, X. Wang, X. Xu, X. Bai, N. Gao, C. Feng, Y. Wei, L. Wu, M. Liu, Synthesis of a starch derivative and its application in fertilizer for slow nutrient release and water-holding, *RSC Adv.* 4 (2014) 51208–51214. doi:10.1039/C4RA06006G.
- [78] A.N. Roziafanto, S. Puspitasari, A. Cifriadi, D. Hasnasoraya, M. Chalid, Addition of Hybrid Coupling Agent Based Natural Rubber-Starch on Natural Rubber Composite, *Macromol. Symp.* 391 (2020) 1–4. doi:10.1002/masy.201900142.
- [79] F. Flores-Céspedes, I. Daza-Fernández, M. Villafranca-Sánchez, M. Fernández-Pérez, E. Morillo, T. Undabeytia, Lignin and ethylcellulose in controlled release formulations to reduce

- leaching of chloridazon and metribuzin in light-textured soils, *J. Hazard. Mater.* 343 (2018) 227–234. doi:10.1016/j.jhazmat.2017.09.012.
- [80] Q. Wu, W. Shao, N. Xia, P. Wang, F. Kong, A separable paper adhesive based on the starch—lignin composite, *Carbohydr. Polym.* 229 (2020) 115488. doi:10.1016/j.carbpol.2019.115488.
- [81] C.A. Gómez-Aldapa, G. Velazquez, M.C. Gutierrez, E. Rangel-Vargas, J. Castro-Rosas, R.Y. Aguirre-Loredo, Effect of polyvinyl alcohol on the physicochemical properties of biodegradable starch films, *Mater. Chem. Phys.* 239 (2020) 122027. doi:10.1016/j.matchemphys.2019.122027.
- [82] S. Mathew, A. Jayakumar, V.P. Kumar, J. Mathew, E.K. Radhakrishnan, One-step synthesis of eco-friendly boiled rice starch blended polyvinyl alcohol bionanocomposite films decorated with in situ generated silver nanoparticles for food packaging purpose, *Int. J. Biol. Macromol.* . 139 (2019) 475–485. doi:10.1016/j.ijbiomac.2019.07.187.
- [83] M.R. Yusof, R. Shamsudin, Y. Abdullah, F. Yalcinkaya, N. Yaacob, Electrospinning of carboxymethyl starch/poly(L-lactide acid) composite nanofiber, *Polym. Adv. Technol.* 29 (2018) 1843–1851. doi:10.1002/pat.4292.
- [84] Linhui Zhu, Y. Liu, B. Zhou, H. Tang, F. Wang, C. Guan, Synthesis and the Swelling Behavior of Sodium Alginate Graft Poly (Acrylic Acid-co-acrylamide)/Graphite Oxide Super Absorbent Composite, *Polym. Sci. - Ser. B.* 61 (2019) 680–690. doi:10.1134/S1560090419050221.
- [85] M. Salimi, E. Motamedi, B. Motesharezedeh, H.M. Hosseini, H.A. Alikhani, Starch-g-poly(acrylic acid-co-acrylamide) composites reinforced with natural char nanoparticles toward environmentally benign slow-release urea fertilizers, *J. Environ. Chem. Eng.* 8 (2020) 103765. doi:10.1016/j.jece.2020.103765.
- [86] J. Cao, Y. Wang, C. He, Y. Kang, J. Zhou, Ionically crosslinked chitosan/poly(acrylic acid) hydrogels with high strength, toughness and antifreezing capability, *Carbohydr. Polym.* 242 (2020) 116420. doi:10.1016/j.carbpol.2020.116420.
- [87] R.R. Palem, K. Madhusudana Rao, T.J. Kang, Self-healable and dual-functional guar gum-grafted-polyacrylamidoglycolic acid-based hydrogels with nano-silver for wound dressings, *Carbohydr. Polym.* 223 (2019) 115074. doi:10.1016/j.carbpol.2019.115074.
- [88] Zia-ud-Din, L. Chen, I. Ullah, P.K. Wang, A.B. Javaid, C. Hu, M. Zhang, I. Ahamd, H. Xiong, Z. Wang, Synthesis and characterization of starch-g-poly(vinyl acetate-co-butyl acrylate) bio-based adhesive for wood application, *Int. J. Biol. Macromol.* . 114 (2018) 1186–1193. doi:10.1016/j.ijbiomac.2018.03.178.

- [89] E. Czarnecka, J. Nowaczyk, Semi-Natural superabsorbents based on Starch-g-poly(acrylic acid): Modification, synthesis and application, *Polymers (Basel)*. 12 (2020) 1–19. doi:10.3390/polym12081794.
- [90] G. Vlase, R. Blajovan, P. Albu, T. Vlase, Study of thermally induced interaction between hydroxyethylcellulose and carboxymethylcellulose with different excipients, *J. Therm. Anal. Calorim.* 130 (2017) 397–402. doi:10.1007/s10973-017-6309-1.
- [91] H.H. Ammar, S. Lajili, N. Sakly, D. Cherif, C. Rihouey, D. Le Cerf, A. Bouraoui, H. Majdoub, Influence of the uronic acid composition on the gastroprotective activity of alginates from three different genus of Tunisian brown algae, *Food Chem.* 239 (2018) 165–171. doi:10.1016/j.foodchem.2017.06.108.
- [92] F. Dranca, M. Oroian, Extraction, purification and characterization of pectin from alternative sources with potential technological applications, *Food Res. Int.* 113 (2018) 327–350. doi:10.1016/j.foodres.2018.06.065.
- [93] C. Colodel, L.C. Vriesmann, R.F. Teófilo, C.L. de Oliveira Petkowicz, Extraction of pectin from ponkan (*Citrus reticulata* Blanco cv. Ponkan) peel: Optimization and structural characterization, *Int. J. Biol. Macromol.* . 117 (2018) 385–391. doi:10.1016/j.ijbiomac.2018.05.048.
- [94] J. Xu, E.F. Krietemeyer, V.M. Boddu, S.X. Liu, W.C. Liu, Production and characterization of cellulose nanofibril (CNF) from agricultural waste corn stover, *Carbohydr. Polym.* 192 (2018) 202–207. doi:10.1016/j.carbpol.2018.03.017.
- [95] H. El Knidri, R. Belaabed, A. Addaou, A. Laajeb, A. Lahsini, Extraction, chemical modification and characterization of chitin and chitosan, *Int. J. Biol. Macromol.* . 120 (2018) 1181–1189. doi:10.1016/j.ijbiomac.2018.08.139.
- [96] M. Yadav, P. Goswami, K. Paritosh, M. Kumar, N. Pareek, V. Vivekanand, Seafood waste: a source for preparation of commercially employable chitin/chitosan materials, *Bioresour. Bioprocess.* 6 (2019) 1–20. doi:10.1186/s40643-019-0243-y.
- [97] C. Inkrod, M. Raita, V. Champreda, N. Laosiripojana, Characteristics of Lignin Extracted from Different Lignocellulosic Materials via Organosolv Fractionation, *Bioenergy Res.* 11 (2018) 277–290. doi:10.1007/s12155-018-9895-2.
- [98] X. Zhu, Q. He, Y. Hu, R. Huang, N. Shao, Y. Gao, A comparative study of structure, thermal degradation, and combustion behavior of starch from different plant sources, *J. Therm. Anal. Calorim.* 132 (2018) 927–935. doi:10.1007/s10973-018-7030-4.
- [99] N. Rhein-Knudsen, M.T. Ale, S. Rasmussen, S.K. Kamp, J.A. Bentil, A.S. Meyer, Alkaline

- extraction of seaweed carrageenan hydrocolloids using cocoa pod husk ash, *Biomass Convers. Biorefinery*. 8 (2018) 577–583. doi:10.1007/s13399-018-0305-y.
- [100] F. Rashid, S. Hussain, Z. Ahmed, Extraction purification and characterization of galactomannan from fenugreek for industrial utilization, *Carbohydr. Polym.* 180 (2018) 88–95. doi:10.1016/j.carbpol.2017.10.025.
- [101] A. Kumar, K.M. Rao, S.S. Han, Application of xanthan gum as polysaccharide in tissue engineering: A review, *Carbohydr. Polym.* 180 (2018) 128–144. doi:10.1016/j.carbpol.2017.10.009.
- [102] C.E. Elhassani, Y. Essamlali, M. Aqlil, A.M. Nzengué, I. Ganetri, M. Zahouily, Urea-impregnated HAP encapsulated by lignocellulosic biomass-extruded composites: A novel slow-release fertilizer, *Environ. Technol. Innov.* 15 (2019) 100403. doi:10.1016/j.eti.2019.100403.
- [103] H. Lu, H. Tian, M. Zhang, Z. Liu, Q. Chen, R. Guan, H. Wang, Water Polishing improved controlled-release characteristics and fertilizer efficiency of castor oil-based polyurethane coated diammonium phosphate, *Sci. Rep.* 10 (2020) 1–10. doi:10.1038/s41598-020-62611-w.
- [104] H. Lu, H. Tian, Z. Liu, M. Zhang, C. Zhao, Y. Guo, R. Guan, Q. Chen, X. Yu, H. Wang, L. Zheng, Polyolefin Wax Modification Improved Characteristics of Nutrient Release from Biopolymer-Coated Phosphorus Fertilizers, *ACS Omega*. 4 (2019) 20402–20409. doi:10.1021/acsomega.9b03348.
- [105] D. Sarmah, N. Karak, Biodegradable superabsorbent hydrogel for water holding in soil and controlled-release fertilizer, *J. Appl. Polym. Sci.* 137 (2020) 1–12. doi:10.1002/app.48495.
- [106] Saruchi, V. Kumar, H. Mittal, S.M. Alhassan, Biodegradable hydrogels of tragacanth gum polysaccharide to improve water retention capacity of soil and environment-friendly controlled release of agrochemicals, *Int. J. Biol. Macromol.* 132 (2019) 1252–1261. doi:10.1016/j.ijbiomac.2019.04.023.
- [107] S. Chen, Y. Han, M. Yang, X. Zhu, C. Liu, H. Liu, H. Zou, Hydrophobically modified water-based polymer for slow-release urea formulation, *Prog. Org. Coatings*. 149 (2020) 105964. doi:10.1016/j.porgcoat.2020.105964.
- [108] J. DE GUZMAN, K. Dela Peña, J. Ytac Dorothy, T. Tumolva, Synthesis and characterization of ionically-crosslinked  $\kappa$ -carrageenan/sodium alginate/carboxymethyl cellulose hydrogel blends for soil water retention and fertilizer release, *Solid State Phenom.* 304 (2020) 59–65. doi:10.4028/www.scientific.net/ssp.304.59.
- [109] T. El Assimi, O. Lakbita, A. El Meziane, M. Khouloud, A. Dahchour, R. Beniazza, R. Boulif,

- M. Raihane, M. Lahcini, Sustainable coating material based on chitosan-clay composite and paraffin wax for slow-release DAP fertilizer, *Int. J. Biol. Macromol.* . 161 (2020) 492–502. doi:10.1016/j.ijbiomac.2020.06.074.
- [110] T. Xu, C. Ma, Z. Aytac, X. Hu, K.W. Ng, J.C. White, P. Demokritou, Enhancing Agrichemical Delivery and Seedling Development with Biodegradable, Tunable, Biopolymer-Based Nanofiber Seed Coatings, *ACS Sustain. Chem. Eng.* 8 (2020) 9537–9548. doi:10.1021/acssuschemeng.0c02696.
- [111] I. Meftah Kadmiri, N. El Mernissi, S.E. Azaroual, M.E.M. Mekhzoum, A.E.K. Qaiss, R. Bouhfid, Bioformulation of Microbial Fertilizer Based on Clay and Alginate Encapsulation, *Curr. Microbiol.* (2020) 1–9. doi:10.1007/s00284-020-02262-2.
- [112] M. Baki, J. Abedi-Koupai, Preparation and characterization of a superabsorbent slow-release fertilizer with sodium alginate and biochar, *J. Appl. Polym. Sci.* 135 (2018). doi:10.1002/app.45966.
- [113] X. Jia, Z.Y. Ma, G.X. Zhang, J.M. Hu, Z.Y. Liu, H.Y. Wang, F. Zhou, Polydopamine film coated controlled-release multielement compound fertilizer based on mussel-inspired chemistry, *J. Agric. Food Chem.* 61 (2013) 2919–2924. doi:10.1021/jf3053059.
- [114] K.T. Morgan, K.E. Cushman, S. Sato, Release mechanisms for slow- and controlled release fertilizers and strategies for their use in vegetable production, *Horttechnology.* 19 (2009) 10–12.
- [115] L. Liu, J. Kost, L. Fishman Marshall, B. Hicks Kevin, A Review: Controlled Release Systems for Agricultural and Food Applications, *New Deliv. Syst. Control. Drug Release from Nat. Occur. Mater.* 992 (2008) 265–281. doi:10.1021/bk-2008-0992.
- [116] S. Fertahi, I. Bertrand, M. Ilsouk, A. Oukarroum, M.B. Amjoud, Y. Zeroual, A. Barakat, New generation of controlled release phosphorus fertilizers based on biological macromolecules : Effect of formulation properties on phosphorus release, *Int. J. Biol. Macromol.* . 143 (2020) 153–162.
- [117] K. Lubkowski, A. Smorowska, B. Grzmil, A. Kozłowska, Controlled-release fertilizer prepared using a biodegradable aliphatic copolyester of poly(butylene succinate) and dimerized fatty acid, *J. Agric. Food Chem.* 63 (2015) 2597–2605. doi:10.1021/acs.jafc.5b00518.
- [118] M. Tomaszewska, A. Jarosiewicz, K. Karakulski, Physical and chemical characteristics of polymer coatings in CRF formulation, *Desalin.* 146 3 19-323. 3 (2002) 19–323. doi:10.1016/S0011-9164(02)00501-5.
- [119] M. Tomaszewska, A. Jarosiewicz, Use of polysulfone in controlled-release NPK fertilizer

- formulations, *J. Agric. Food Chem.* 50 (2002) 4634–4639. doi:10.1021/jf0116808.
- [120] S.-A. Riyajana, Y. Sasithornsontia, P. Pranee, Green natural rubber-g-modified starch for controlling urea release, *Adv. Agron.* 71 (2000) 1–49. doi:10.1016/j.carbpol.2012.03.004.
- [121] A.M. Agrawal, P. Pandey, Scale Up of Pan Coating Process Using Quality by Design Principles, *J. Pharm. Sci.* 104 (2015) 3589–3611. doi:10.1002/jps.24582.
- [122] M.Y. Naz, S.A. Sulaiman, Slow release coating remedy for nitrogen loss from conventional urea: A review, *J. Control. Release.* 225 (2016) 109–120. doi:10.1016/j.jconrel.2016.01.037.
- [123] J. Li, M. Wang, D. She, Y. Zhao, Structural functionalization of industrial softwood kraft lignin for simple dip-coating of urea as highly efficient nitrogen fertilizer, *Ind. Crops Prod.* 109 (2017) 255–265. doi:10.1016/j.indcrop.2017.08.011.
- [124] T.H. Nguyen, M.N.T. An, M. Alam, N. Tran, D. V. Trinh, Empirical scale-up model of pan-coating process for controlled-release urea fertilizer production, *Part. Sci. Technol.* (2020) 1–8. doi:10.1080/02726351.2020.1841348.
- [125] F.E. Babadi, R. Yunus, A. Abbasi, S.M. Soltani, Response surface method in the optimization of a rotary pan-equipped process for increased efficiency of slow-release coated urea, *Processes.* 7 (2019) 1–16. doi:10.3390/pr7030125.
- [126] H. Sedighikamal, R. Zarghami, P. Khadiv-Parsi, N. Mostoufi, Sustained release coating of ibuprofen pellets at Wurster fluidization: statistical approach, *J. Pharm. Investig.* 45 (2015) 341–347. doi:10.1007/s40005-015-0177-0.
- [127] Y. Wang, H. Guo, X. Wang, Z. Ma, X. Li, R. Li, Q. Li, R. Wang, X. Jia, Spout Fluidized Bed Assisted Preparation of Poly(tannic acid)-Coated Urea Fertilizer, *ACS Omega.* 5 (2020) 1127–1133. doi:10.1021/acsomega.9b03310.
- [128] B. Azeem, K.Z. KuShaari, Z. Man, T.H. Trinh, Effect of fluidized-bed process variables on controlled-release of nitrogen and coating, *Brazilian J. Chem. Eng.* 35 (2018) 587–603. doi:10.1590/0104-6632.20180352s20160424.
- [129] A. van Kampen, R. Kohlus, Systematic process optimisation of fluid bed coating, *Powder Technol.* 305 (2017) 426–432. doi:10.1016/j.powtec.2016.10.007.
- [130] D. Müller, A. Bück, E. Tsotsas, Influence of separation properties and processing strategies on product characteristics in continuous fluidized bed spray granulation, *Powder Technol.* 342 (2019) 572–584. doi:10.1016/j.powtec.2018.10.024.
- [131] E. Sahni, B. Chaudhuri, Experimental and modeling approaches in characterizing coating uniformity in a pan coater: A literature review, *Pharm. Dev. Technol.* 17 (2012) 134–147.

doi:10.3109/10837450.2011.649852.

- [132] S.R.L. Werner, J.R. Jones, A.H.J. Paterson, R.H. Archer, D.L. Pearce, Air-suspension particle coating in the food industry: Part I - state of the art, *Powder Technol.* 171 (2007) 25–33. doi:10.1016/j.powtec.2006.08.014.
- [133] S. Fertahi, I. Bertrand, M. Amjoud, A. Oukarroum, M. Arji, A. Barakat, Properties of Coated Slow-Release Triple Superphosphate (TSP) Fertilizers Based on Lignin and Carrageenan Formulations, *ACS Sustain. Chem. Eng.* 7 (2019) 10371–10382. doi:10.1021/acssuschemeng.9b00433.
- [134] Y. Niu, H. Li, Controlled Release of Urea Encapsulated by Starch-g-poly(vinyl acetate), *Eng. Chem. Res.* 51 (2012) 12173–12177. doi:10.1021/ie301684p.
- [135] M. Fernández-Pérez, F.J. Garrido-Herrera, E. González-Pradas, M. Villafranca-Sánchez, F. Flores-Céspedes, Lignin and ethylcellulose as polymers in controlled release formulations of urea, *J. Appl. Polym. Sci.* 108 (2008) 3796–3803. doi:10.1002/app.27987.
- [136] B. Beig, M.B.K. Niazi, Z. Jahan, S.J. Kakar, G.A. Shah, M. Shahid, M. Zia, M.U. Haq, M.I. Rashid, Biodegradable polymer coated granular urea slows down n release kinetics and improves spinach productivity, *Polymers (Basel)*. 12 (2020) 1–19. doi:10.3390/polym12112623.
- [137] Y. Kusumastuti, A. Istiani, Rochmadi, C.W. Purnomo, Chitosan-Based Polyion Multilayer Coating on NPK Fertilizer as Controlled Released Fertilizer, *Adv. Mater. Sci. Eng.* (2019) 2958021. doi:10.1155/2019/2958021.
- [138] Y. Cui, Y. Xiang, Y. Xu, J. Wei, Z. Zhang, L. Li, J. Li, Poly-acrylic acid grafted natural rubber for multi-coated slow release compound fertilizer: Preparation, properties and slow-release characteristics, *Int. J. Biol. Macromol.* . 146 (2020) 540–548. doi:10.1016/j.ijbiomac.2020.01.051.
- [139] D. Qiao, H. Liu, L. Yu, X. Bao, G.P. Simon, E. Petinakis, L. Chen, Preparation and characterization of slow-release fertilizer encapsulated by starch-based superabsorbent polymer, *Carbohydr. Polym.* 147 (2016) 146–154. doi:10.1016/j.carbpol.2016.04.010.
- [140] W. Jing, L.I.U. Song, Q.I.N. Yukun, Preparation and characterization of controlled-release fertilizers coated with marine polysaccharide derivatives \*, *Chinese J. Oceanol. Limnol.* (2016) 1–8.
- [141] H. Li, L. Sui, Y. Niu, Preparation and Properties of a Double-Coated Slow-Release Urea Fertilizer with Poly ( propylene carbonate ), a Sodium Polyacrylate Hydroscopicity Resin and Sodium Alginate, *Mater. Sci. Inc. Nanomater. Polym. Prep.* 3 (2018) 7643–7647.

doi:10.1002/slct.201800913.

- [142] S. Noppakundilokrat, N. Pheatcharat, S. Kiatkamjornwong, Multilayer-coated NPK compound fertilizer hydrogel with controlled nutrient release and water absorbency, *J. Appl. Polym. Sci.* 132 (2015) 1–11. doi:10.1002/app.41249.
- [143] L.L. Messa, R. Faez, Spray-dried chitosan/nanocellulose microparticles: synergistic effects for the sustained release of NPK fertilizer, *Cellulose*. 2 (2020) 1–17. doi:10.1007/s10570-020-03482-2.
- [144] N.N.R. Ahmad, W.J.N. Fernando, M.H. Uzir, Parametric evaluation using mechanistic model for release rate of phosphate ions from chitosan-coated phosphorus fertiliser pellets, *Biosyst. Eng.* 129 (2015) 78–86. doi:10.1016/j.biosystemseng.2014.09.015.
- [145] L. Wu, M. Liu, Rui Liang, Preparation and properties of a double-coated slow-release NPK compound fertilizer with superabsorbent and water-retention, *Bioresour. Technol.* 99 (2008) 547–554. doi:10.1016/j.biortech.2006.12.027.
- [146] B. Ni, M. Liu, S. Lu, L. Xie, Y. Wang, Multifunctional slow-release organic-inorganic compound fertilizer, *J. Agric. Food Chem.* 58 (2010) 12373–12378. doi:10.1021/jf1029306.
- [147] R. Liang, M. Liu, Preparation and properties of a double-coated slow-release and water-retention urea fertilizer, *J. Agric. Food Chem.* 54 (2006) 1392–1398. doi:10.1021/jf052582f.
- [148] Y. Wang, M. Liu, B. Ni, L. Xie, K-Carrageenan-sodium alginate beads and superabsorbent coated nitrogen fertilizer with slow-release, water-retention, and anticompaction properties, *Ind. Eng. Chem. Res.* 51 (2012) 1413–1422. doi:10.1021/ie2020526.
- [149] X. Wang, S. Lu, C. Gao, X. Xu, Y. Wei, X. Bai, C. Feng, N. Gao, M. Liu, L. Wu, Biomass-based multifunctional fertilizer system featuring controlled-release nutrient, water-retention and amelioration of soil, *RSC Adv.* 4 (2014) 18382. doi:10.1039/c4ra00207e.
- [150] M. Guo, M. Liu, F. Zhan, L. Wu, Preparation and properties of a slow-release membrane-encapsulated urea fertilizer with superabsorbent and moisture preservation, *Ind. Eng. Chem. Res.* 44 (2005) 4206–4211. doi:10.1021/ie0489406.
- [151] A. Sofyane, E. Ablouh, M. Lahcini, A. Elmeziane, M. Khoulood, H. Kaddami, M. Raihane, Materials Today : Proceedings Slow-release fertilizers based on starch acetate / glycerol / polyvinyl alcohol biocomposites for sustained nutrient release, *Mater. Today Proc.* (2020). doi:10.1016/j.matpr.2020.05.319.
- [152] M. Zhang, J. Yang, Preparation and characterization of multifunctional slow release fertilizer coated with cellulose derivatives, *Int. J. Polym. Mater. Polym. Biomater.* (2020) 1–8.

doi:10.1080/00914037.2020.1765352.

- [153] K. Lubkowski, A. Smorowska, M. Sawicka, E. Wróblewska, A. Dzienisz, M. Sad, Ethylcellulose as a coating material in controlled-release fertilizers, , 2019 Polish J. Chem. Technol. 21 (2019) 52–58.
- [154] R.A. Ramli, Y.M. Lian, N.M. Nor, N.I.Z. Azman, Synthesis , characterization , and morphology study of coco peat- grafted -poly ( acrylic acid )/ NPK slow release fertilizer hydrogel, J. Polym. Res. 26 (2019) 1–7.
- [155] S. Fertahi, I. Bertrand, M. Ilsouk, A. Oukarroum, M. Amjoud, Y. Zeroual, A. Barakat, Impact of Plasticizers on Lignin-Carrageenan Formulation Properties and on Phosphorus Release from a Coated Triple Superphosphate Fertilizer, Ind. Eng. Chem. Res. 59 (2020) 14172–14179. doi:10.1021/acs.iecr.0c03143.
- [156] S. Fertahi, I. Bertrand, M. Amjoud, A. Oukarroum, M. Arji, A. Barakat, Properties of Coated Slow-Release Triple Superphosphate (TSP) Fertilizers Based on Lignin and Carrageenan Formulations, ACS Sustain. Chem. Eng. 7 (2019) 10371–10382. doi:10.1021/acssuschemeng.9b00433.
- [157] E.R. Kenawy, M.M. Azaam, E.M. El-nshar, Preparation of carboxymethyl cellulose - g - poly ( acrylamide )/ montmorillonite superabsorbent composite as a slow - release urea fertilizer, Polym. Adv. Technol. (2018) 1–8. doi:10.1002/pat.4315.
- [158] Y.X. Huang, M.J. Liu, S. Chen, I.I. Jasmi, Y. Tang, S. Lin, Enhanced adsorption and slow release of phosphate by dolomite – alginate composite beads as potential fertilizer, Water Environ. Fed. 91 (2019) 797–804. doi:10.1002/wer.1122.
- [159] E. Kenawy, M.M. Azaam, E.M. El-nshar, Sodium alginate-g-poly ( acrylic acid-co-2-hydroxyethyl methacrylate )/ montmorillonite superabsorbent composite : Preparation , swelling investigation and its application as a slow-release fertilizer, Arab. J. Chem. 12 (2019) 847–856. doi:10.1016/j.arabjc.2017.10.013.
- [160] I. Sathisaran, M. Balasubramanian, Heliyon Physical characterization of chitosan / gelatin-alginate composite beads for controlled release of urea, Heliyon. 6 (2020) e05495. doi:10.1016/j.heliyon.2020.e05495.
- [161] T. El Assimi, M. Chaib, M. Raihane, A. El Meziane, M. Khoulood, R. Benhida, 2 Redouane Beniazza2 · Mohammed Lahcini1, Poly ( ε - caprolactone )- g - Guar Gum and Poly ( ε - caprolactone )- g - Halloysite Nanotubes as Coatings for Slow - Release DAP Fertilizer, J. Polym. Environ. 28 (2020) 2078–2090. doi:10.1007/s10924-020-01750-7.

- [162] X. Wang, X. Zhang, X. Hu, Z. Jin, Performance adjustable porous polylactic acid-based membranes for controlled release fertilizers, *J. Appl. Polym. Sci.* (2020) 1–12. doi:10.1002/app.49649.
- [163] F. Rotondo, R. Coniglio, L. Cantera, I. Di Pascua, L. Clavijo, A. Dieste, Lignin-based coatings for controlled P-release fertilizer consisting of granulated simple superphosphate, *Holzforschung*. 72 (2018) 637–643. doi:10.1515/hf-2017-0176.
- [164] H. Qi, R. Ma, C. Shi, Z. Huang, S. Liu, L. Sun, T. Hu, International Journal of Biological Macromolecules Novel low-cost carboxymethyl cellulose microspheres with excellent fertilizer absorbency and release behavior for saline-alkali soil Saline-alkali soil, *Int. J. Biol. Macromol.* . 131 (2019) 412–419. doi:10.1016/j.ijbiomac.2019.03.047.
- [165] G. Rozo, L. Bohorques, J. Santamaría, Controlled release fertilizer encapsulated by a  $\kappa$ -carrageenan hydrogel, *Polim. Ciência e Tecnol.* 29 (2019) e2019033.
- [166] A. Sofyane, M. Lahcini, A. El, M. Mehdi, Properties of Coated Controlled Release Diammonium Phosphate Fertilizers Prepared with the Use of Bio-based Amino Oil, *J Am Oil Chem Soc.* (2020) 1–13. doi:10.1002/aocs.12360.
- [167] B. Ni, S. Lu, M. Liu, Novel multinutrient fertilizer and its effect on slow release, water holding, and soil amending, *Ind. Eng. Chem. Res.* 51 (2012) 12993–13000. doi:10.1021/ie3003304.
- [168] K. Zhang, Z. Wang, Q. Xu, B. Liu, M. Duan, L. Wang, Effect of controlled-release urea fertilizers for oilseed rape (*Brassica napus* L.) on soil carbon storage and CO<sub>2</sub> emission, *Environ. Sci. Pollut. Res.* (2020) 1–12.
- [169] P. Nardi, U. Neri, G.D.I. Matteo, A. Trinchera, R. Napoli, R. Farina, G. V Subbarao, A. Benedetti, Nitrogen Release from Slow-Release Fertilizers in Soils with Different Microbial Activities, *Pedosphere*. 28 (2018) 332–340. doi:10.1016/S1002-0160(17)60429-6.
- [170] K. Inubushi, S. Acquaye, S. Tsukagoshi, F. Shibahara, S. Komatsu, Effects of controlled-release coated urea (CRCU) on soil microbial biomass N in paddy fields examined by the <sup>15</sup>N tracer technique, *Nutr. Cycl. Agroecosystems*. 63 (2002) 291–300. doi:10.1023/A:1021111126976.
- [171] H.Y. Chu, Y. Hosen, K. Yagi, K. Okada, O. Ito, Soil microbial biomass and activities in a Japanese Andisol as affected by controlled release and application depth of urea, *Biol. Fertil. Soils*. 42 (2005) 89–96. doi:10.1007/s00374-005-0011-3.
- [172] S. Acquaye, K. Inubushi, Comparative effects of application of coated and non-coated urea in clayey and sandy paddy soil microcosms examined by the N-15 tracer technique, *Soil Sci. Plant Nutr.* 50 (2004) 205–213. doi:10.1080/00380768.2004.10408469.

- [173] M.C. Garcia, J.A. Díez, A. Vallejo, L. García, M.C. Cartagena, Effect of Applying Soluble and Coated Phosphate Fertilizers on Phosphate Availability in Calcareous Soils and on P Absorption by a Rye-Grass Crop, *J. Agric. Food Chem.* 45 (1997) 1931–1936. doi:10.1021/jf960600a.
- [174] J.A. Diez, M.C. Cartagena, A. Vallejo, Controlling phosphorus fixation in calcareous soils by using coated diammonium phosphate, *Fertil. Res.* 31 (1992) 269–274. doi:10.1007/BF01051278.
- [175] R.H. McKenzie, E. Bremer, A.B. Middleton, P.G. Pfiffner, R.E. Dowbenko, Controlled-release urea for winter wheat in southern Alberta, *Can. J. Soil Sci.* 87 (2007) 85–91. doi:10.4141/S06-055.
- [176] M. Zhang, M. Nyborg, S.S. Malhi, E.D. Solberg, Yield and protein content of barley as affected by release rate of coated urea and rate of nitrogen application, *J. Plant Nutr.* 23 (2000) 401–412. doi:10.1080/01904160009382026.
- [177] D.F. Da Cruz, R. Bortoletto-Santos, G.G.F. Guimarães, W.L. Polito, C. Ribeiro, Role of Polymeric Coating on the Phosphate Availability as a Fertilizer: Insight from Phosphate Release by Castor Polyurethane Coatings, *J. Agric. Food Chem.* 65 (2017) 5890–5895. doi:10.1021/acs.jafc.7b01686.
- [178] R.C. de Castro, V. de Melo Benites, P. César Teixeira, M.J. dos Anjos, L.F. de Oliveira, Phosphorus migration analysis using synchrotron radiation in soil treated with Brazilian granular fertilizers, *Appl. Radiat. Isot.* 105 (2015) 233–237. doi:10.1016/j.apradiso.2015.08.036.
- [179] E. Lombi, M.J. McLaughlin, C. Johnston, R.D. Armstrong, R.E. Holloway, Mobility, solubility and lability of fluid and granular forms of P fertiliser in calcareous and non-calcareous soils under laboratory conditions, *Plant Soil.* 269 (2005) 25–34. doi:10.1007/s11104-004-0558-z.
- [180] K. Lawton, J.A. Vomocil, The Dissolution and Migration of Phosphorus from Granular Superphosphate in Some Michigan Soils, *Soil Sci. Soc. Am. J.* 18 (1954) 26–32. doi:10.2136/sssaj1954.03615995001800010008x.
- [181] F.F. Montesano, A. Parente, P. Santamaria, A. Sannino, F. Serio, Biodegradable Superabsorbent Hydrogel Increases Water Retention Properties of Growing Media and Plant Growth, *Agric. Agric. Sci. Procedia.* 4 (2015) 451–458. doi:10.1016/j.aaspro.2015.03.052.
- [182] A.T.P. Tran, I. Chang, G.C. Cho, Soil water retention and vegetation survivability improvement using microbial biopolymers in drylands, *Geomech. Eng.* 17 (2019) 475–483. doi:10.12989/gae.2019.17.5.475.

- [183] R. Liang, M. Liu, L. Wu, Controlled release NPK compound fertilizer with the function of water retention, *React. Funct. Polym.* 67 (2007) 769–779. doi:10.1016/j.reactfunctpolym.2006.12.007.
- [184] B. Ni, M. Liu, S. Lu, L. Xie, Y. Wang, Environmentally friendly slow-release nitrogen fertilizer, *J. Agric. Food Chem.* 59 (2011) 10169–10175. doi:10.1021/jf202131z.
- [185] W. Lan, L. Mingzhu, Preparation and characterization of cellulose acetate-coated compound fertilizer with controlled-release and water-retention, *Polym. Adv. Technol.* 19 (2008) 785–792. doi:10.1002/pat.
- [186] L. Xie, M. Liu, B. Ni, Y. Wang, Utilization of wheat straw for the preparation of coated controlled-release fertilizer with the function of water retention, *J. Agric. Food Chem.* 60 (2012) 6921–6928. doi:10.1021/jf3001235.
- [187] A. Niekraszewicz, M. Wiśniewska-Wrona, E. Kopania, L. Orlikowski, H. Pospieszny, K. Krawczyk, Biopolymer compositions for ecological protection and growth stimulation of plants, *Prog. Chem. Appl. Chitin Its Deriv.* (2012) 145–158.
- [188] R. V. Kumaraswamy, S. Kumari, R.C. Choudhary, A. Pal, R. Raliya, P. Biswas, V. Saharan, Engineered chitosan based nanomaterials: Bioactivities, mechanisms and perspectives in plant protection and growth, *Int. J. Biol. Macromol.* 113 (2018) 494–506. doi:10.1016/j.ijbiomac.2018.02.130.
- [189] J.L. Shamshina, T.O. Konak, R.D. Rogers, Applications of Chitin in Agriculture, *Sustain. Agric. Rev.* (2019) 125–146. doi:10.1007/978-3-030-16581-9.
- [190] R. Sharp, A Review of the Applications of Chitin and Its Derivatives in Agriculture to Modify Plant-Microbial Interactions and Improve Crop Yields, *Agronomy.* 3 (2013) 757–793. doi:10.3390/agronomy3040757.
- [191] L. Lucini, Y. Rouphael, M. Cardarelli, P. Bonini, C. Baffi, G. Colla, A vegetal biopolymer-based biostimulant promoted root growth in melon while triggering brassinosteroids and stress-related compounds, *Front. Plant Sci.* 9 (2018) 1–11. doi:10.3389/fpls.2018.00472.
- [192] P. Qian, J. Schoenau, Effects of conventional and controlled release phosphorus fertilizer on crop emergence and growth response under controlled environment conditions, *J. Plant Nutr.* 33 (2010) 1253–1263. doi:10.1080/01904167.2010.484087.
- [193] C. Tian, X. Zhou, Q. Liu, J. wei Peng, W. ming Wang, Z. hua Zhang, Y. Yang, H. xing Song, C. yun Guan, Effects of a controlled-release fertilizer on yield, nutrient uptake, and fertilizer usage efficiency in early ripening rapeseed (*Brassica napus* L.), *J. Zhejiang Univ. Sci. B.* 17 (2016) 775–786. doi:10.1631/jzus.B1500216.

- [194] T.D. Landis, R.K. Dumroese, Using polymer-coated controlled-release fertilizers in the nursery and after outplanting, *For. Nurs. Notes.* (2009) 5–12.
- [195] A.B. Middleton, E. Bremer, R.H. McKenzie, Winter wheat response to nitrogen fertilizer form and placement in southern Alberta, *Can. J. Soil Sci.* 84 (2004) 125–131. doi:10.4141/S03-028.
- [196] A.G. Cunha, C.S.R. Freire, A.J.D. Silvestre, C.P. Neto, A. Gandini, E. Orblin, P. Fardim, Highly hydrophobic biopolymers prepared by the surface pentafluorobenzoylation of cellulose substrates, *Biomacromolecules.* 8 (2007) 1347–1352. doi:10.1021/bm0700136.
- [197] L. Chen, Z. Xie, X. Zhuang, X. Chen, X. Jing, Controlled release of urea encapsulated by starch-g-poly(l-lactide), *Carbohydr. Polym.* 72 (2008) 342–348. doi:10.1016/j.carbpol.2007.09.003.
- [198] K. Zhong, Z.T. Lin, X.L. Zheng, G.B. Jiang, Y.S. Fang, X.Y. Mao, Z.W. Liao, Starch derivative-based superabsorbent with integration of water-retaining and controlled-release fertilizers, *Carbohydr. Polym.* 92 (2013) 1367–1376. doi:10.1016/j.carbpol.2012.10.030.
- [199] F. Ramirez-Cano, A. Ramos-quirarte, O. Faix, D. Meier, Slow-release effect of N-functionalized kraft lignin tested with Sorghum over two growth periods, *Bioresour. Technol.* 76 (2001) 71–73. doi:10.1016/S0960-8524(00)00066-3.
- [200] D.S. Bajwa, G. Pourhashem, A.H. Ullah, S.G. Bajwa, A concise review of current lignin production, applications, products and their environmental impact, *Ind. Crops Prod.* 139 (2019) 111526. doi:10.1016/j.indcrop.2019.111526.
- [201] D. Martin-Ortiz, L. Herna Ndez-Apaolaza, A. Garate, Efficiency of a NPK Fertilizer with Adhered Zinc Lignosulfonate as a Zinc Source for Maize ( *Zea mays L.* ), *J. Agric. Food Chem.* 57 (2009) 9071–9078. doi:10.1021/jf9017965.
- [202] G. Jiao, Q. Xu, S.-L. Cao, P. Pai, D. She, Urea / Hydroxymethylurea / Urea-Formaldehyde Polymers, *BioResources.* 13 (2018) 1711–1728. doi:10.15376/biores.13.1.1711-1728.
- [203] K. Wang, J. Chen, S.-N. Sun, R.-C. Sun, Steam Explosion, *Pretreat. Biomass.* (2015) 76–104. doi:10.1016/B978-0-12-800080-9.00006-2.
- [204] A. Ramirez, G. Varela, E. Delgado, F. Lopez-Dellamary, V. Zuniga, V. Gonzalez, O. Faix, D. Meier, Reactions , characterization and uptake of ammoxidized kraft lignin labeled with 15 N, *Bioresour. Technol.* 98 (2007) 1494–1500. doi:10.1016/j.biortech.2005.08.004.
- [205] Y. Matsushita, S. Yasuda, Reactivity of a condensed – type lignin model compound in the Mannich reaction and preparation of cationic surfactant from sulfuric acid lignin, *J. Wood Sci.* 49 (2003) 166–171.

- [206] L. Hu, H. Pan, Y. Zhou, M. Zhang, Methods to improve lignin's reactivity as a phenol substitute and as replacement for other phenolic compounds: a brief review, *Bioresources*. 6 (2011) 3515–3525.
- [207] T. Malutan, R. Nicu, V.I. Popa, Contribution to the study of hydroxymetylation reaction of alkali lignin, *BioResources*. 3 (2008) 13–20. doi:10.15376/biores.3.1.13-20.

