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## Plastoquinone in and beyond photosynthesis

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1 **Review**

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4 **Plastoquinone in and beyond photosynthesis**

5

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16 **Keywords** : plastoquinone, photosynthetic electron transport, photooxidative stress,

17 antioxidant, reactive oxygen species, chloroplast metabolism

18

19

20 **Abstract**

21 Plastoquinone-9 is an essential component of photosynthesis, carrying electrons in the linear  
22 and alternative electron transport chains, and a redox sensor regulating state transitions and  
23 gene expression. However, a large fraction of the plastoquinone pool is located outside the  
24 thylakoid membranes, in the plastoglobules and the chloroplast envelopes, reflecting a wide  
25 range of functions beyond electron transport. Here we describe new functions of  
26 plastoquinone in photoprotection, as a potent antioxidant, and in chloroplast metabolism, as  
27 a co-factor in the biosynthesis of chloroplastic metabolites. We point out the requirement  
28 for a tight environmental control of plastoquinone biosynthesis and for active exchange of  
29 this compound between the thylakoid membranes and the plastoglobules. Through its  
30 multiple functions, plastoquinone connects photosynthesis with metabolism, light  
31 acclimation and stress tolerance.

32

33 **Plastoquinone-9 and its Variants in Plants**

34 Plastoquinone (PQ) is an essential component of the chloroplasts in plants, being involved in  
35 photosynthetic electron transport. Plants deficient in PQ are impaired in photosynthesis and  
36 therefore they are not viable photoautotrophically or suffer pleiotropic effects [1,2]. The  
37 basic structure of PQ is a benzoquinonic ring attached to a polyisoprenoid side chain. The  
38 main form of PQ in plants is PQ-9 which contains a nonaprenyl side chain (Fig. 1). However,  
39 some minor PQ forms with shorter side chains were reported in some plant species, such as  
40 PQ-3, PQ-4 and PQ-8 [3-5]. Plants can also contain small amounts of  
41 demethylplastoquinones [5] as well as several forms generated by non-enzymatic oxidation  
42 of PQ-9, especially by singlet oxygen ( $^1\text{O}_2$ ) oxidation, such as hydroxyplastoquinone (PQ-C),  
43 containing one hydroxyl group in the prenyl side chain [3,6] and trihydroxyplastoquinone  
44 with three hydroxyl groups [7]. The fatty acid ester of PQ-C, named PQ-B, has also been  
45 found in small amounts in arabidopsis leaves (*Arabidopsis thaliana*) under high light stress  
46 [8]. Similarly to PQ-9, both PQ-B and PQ-C can function as electron acceptors of photosystem  
47 II (PSII) in thylakoid membranes [9]. Recent details of other important functions for PQ has  
48 come to light, such as photoprotection, antioxidant reservoir or metabolite biosynthesis,  
49 which are described in this review.

50

## 51 **PQ Biosynthesis**

52 The biosynthetic pathway of PQ-9 is composed of two main stages [5,10,11]. The first stage  
53 leads to the biosynthesis of precursors of the benzoquinone ring and of the prenyl side  
54 chain. The second stage includes the condensation of ring and side chain and subsequent  
55 modifications (Fig. 2).

56

57 The benzene quinone ring precursor for PQ-9 is homogentisic acid synthesized from tyrosine  
58 by the enzymes TYROSINE AMINOTRANSFERASE and 4-HYDROXYPHENYLPYRUVATE  
59 REDUCTASE. On the other hand, the prenyl side chain is synthesized from glyceraldehyde 3-  
60 phosphate and pyruvate through the methylerythritol 4-phosphate (MEP) pathway in the  
61 chloroplasts and/or from Acetyl-coA through the mevalonate (MVA) pathway in the  
62 cytoplasm. Through these pathways, PQ-9 biosynthesis is linked to the isoprenoid pathway  
63 that leads to the synthesis of carotenoids and chlorophylls [12,13]. The resulting isoprene  
64 precursor IPP (isopentenyl-pyrophosphate) and its isomer DMAPP (dimethylallyl-  
65 pyrophosphate) are converted into intermediate diphosphate precursors that ultimately  
66 lead to the C<sub>45</sub> solanesyl diphosphate through the catalytic action of SOLANESYL  
67 DIPHOSPHATE SYNTHASE (SPS). In arabidopsis, the latter enzyme could form a complex with  
68 FIBRILLIN 5, possibly to facilitate release of the solanesyl moiety from the enzyme [14]. In  
69 the second stage, solanesyl diphosphate is attached to homogentisate by HOMOGENTISATE  
70 SOLANESYL TRANSFERASE, leading to the intermediate 2-dimethylplastoquinone which is  
71 converted to PQ-9 through the catalytic activity of VTE3 (phytylbenzoquinol  
72 methyltransferase). Finally, a fraction of the PQ-9 pool can be converted to  
73 plastochromanol-8 under the catalysis of VTE1 (tocopherol cyclase) [15].

74

75 The PQ-9 biosynthesis pathway is parallel to the biosynthesis pathway of tocopherol (vitamin  
76 E), sharing a number of common enzymes such as VTE3 and VTE1 (Fig. 2). In the latter  
77 pathway, homogentisate is condensed to phytyldiphosphate to generate MPBQ (2-methyl-6-  
78 phytyl-1, 4-benzoquinol) which is converted to  $\alpha$ -tocopherol via the action of VTE3, VTE1  
79 and VTE4 ( $\gamma$ -tocopherol methyltransferase). Condensation of homogentisate with  
80 geranylgeranyl diphosphate leads to  $\alpha$ -tocotrienol, a unsaturated forms of vitamin E,  
81 through the sequential activity fo VTE3, VTE1 and VTE4 (Fig. 2). The various steps of PQ-9

82 and tocopherol biosyntheses occur in different compartments of the chloroplast, therefore  
83 requiring their tight cooperation as well as complex transport systems [16].

84

### 85 **Regulation of PQ Content in Plants**

86 Although the environmental regulation of PQ-9 content in plants is poorly documented, the  
87 PQ-9 levels appear to be highly responsive to changes in the environmental conditions. For  
88 instance, when grown in high light, arabidopsis plants accumulated high PQ-9 levels  
89 compared to low light conditions [15,17]. In sun-exposed leaves of beech and fig tree, a  
90 considerable accumulation of PQ-9 was observed throughout the vegetation period from  
91 Spring to Summer [11]. This phenomenon was less marked for tocopherols. When  
92 Arabidopsis plants were transferred from low light to high light, a transitory depletion of PQ-  
93 9 occurred, followed by a considerable accumulation which was not observed for  
94 tocopherols [18]. Accordingly, labelling studies with  $^{14}\text{C}$  showed that PQ has a much faster  
95 turnover than tocopherols [19]. The *in vivo* half-life of PQ was also reported to be much  
96 shorter than that of ubiquinone [20]. PQ-9 losses in high light-exposed leaves were  
97 accompanied by the accumulation of oxidized forms of PQ-9 such as (multi)hydroxylated PQs  
98 [7]. Moreover, high light-induced loss of PQ-9 in arabidopsis leaves was found to be  
99 drastically enhanced in a  $^1\text{O}_2$ -overproducing mutant (*ch1*), suggesting a role for this ROS in  
100 PQ-9 photodegradation [18]. Genes coding for enzymes of the PQ-9 biosynthetic pathway  
101 were induced during light acclimation [18,21], in line with PQ-9 accumulation. In microalgae  
102 too, high light induced PQ-9 accumulation which is attributable to a stimulated biosynthesis  
103 as indicated by the net loss of PQ-9 in the presence of pyrazolate, a PQ-9 synthesis inhibitor  
104 [22]. High temperature is another factor that has been reported to trigger PQ-9 and  
105 plastochromanol-8 accumulation in leaves [23]. However, the combination of high light and  
106 low temperature was found to be the most effective to induce the expression of the *VTE1*  
107 and *VTE4* genes and to cause PQ-9 accumulation [24]. This condition is known to promote  
108 high excitation pressure on the photosystems, ROS production and photooxidative stress  
109 [25].

110

111 The picture emerging from those data is that PQ-9 is consumed under oxidative stress  
112 conditions, presumably as a result of ROS scavenging by PQ-9 (see below), and that marked  
113 stimulation of *de novo* biosynthesis can counterbalance this phenomenon, finally resulting in

114 increased PQ-9 levels when plants are acclimated to the prevailing stress conditions.  
115 Moreover, large accumulations of PQ-9 under pro-oxidative environmental conditions  
116 support the idea that this compound plays a protective role against oxidative stress in plants.  
117

### 118 **PQ Localization in Plant Cells**

119 PQ-9 is a lipid-soluble compound located in different lipidic structures of the chloroplasts:  
120 the thylakoid membranes, the plastoglobules and the chloroplastic envelopes [17,26,27].  
121 Small amounts of PQ-9 were also reported in root plastids [28]. In normal growth conditions,  
122 up to 50% of the PQ-9 pool in plant leaves is located in the thylakoid membranes where it  
123 participates in electron transport from PSII to the cytochrome b6/f. The number of PQ-9  
124 molecules per PSII has been estimated to be around 10-15 [27,29,30] although some lower  
125 values were reported [31]. The total PQ-9 concentration in plants can vary considerably with  
126 the environmental conditions, but the amount of photochemically active PQ-9 in the  
127 thylakoid membrane seems to be rather constant [27], possibly representing an optimal  
128 value for photosynthesis. As a corollary, the PQ-9 pool is predominantly located outside the  
129 thylakoid membranes, *i.e.* the plastoglobules and the envelopes, under stress conditions that  
130 induce strong accumulations of PQ-9. This could be related to the dense packing of thylakoid  
131 membranes with proteins, with an estimated occupancy of 70-80% [32], likely restricting PQ-  
132 9 diffusion. An organization of the photosynthetic electron chain in supercomplexes has  
133 been hypothesized, involving microdomains of PSII, PQ-9 and cytochrome b6/f which  
134 facilitate rapid diffusion of mobile PQ-9 over short distances in the thylakoid grana [33].  
135 Possibly, these microdomains of PSII and cytochrome b6/f complexes may accommodate a  
136 limited number of PQ-9 molecules involved in rapid exchange between the two complexes.  
137 Such localization of PQ-9 in small microdomains could explain why the reduction rate of  
138 flash-oxidized cytochrome f is unaffected by the fatty acid saturation levels and the bulk lipid  
139 fluidity of the thylakoid membranes [34]. Consequently, under conditions that can induce  
140 marked accumulations of PQ-9 (*e.g.* high light), the extra PQs are stored in the  
141 plastoglobules which function as PQ reservoirs [27]. A similar phenomenon was observed  
142 when PQ-9 biosynthesis was artificially boosted by overexpressing SPS1: the PQ-9  
143 concentration in the thylakoid membranes was virtually unchanged compared to the wild  
144 type while the size of the photochemically non-active pool outside the thylakoid membrane  
145 (plastoglobules, envelopes) was strongly enhanced [18]. This multi-site localization of PQ-9

146 may indicate multiple functions for this molecule, going beyond its 'traditional' role in  
147 photosynthetic electron transport.

148

#### 149 **PQ in Photosynthesis**

150 PQ-9 has long been viewed exclusively as a photosynthetic electron carrier, shuttling  
151 electrons from PSII to cytochrome b6/f [35,36]. In brief, a PQ-9 molecule firmly bound to the  
152 Q<sub>A</sub> site of the PSII protein D1 transfers electrons between pheophytin and another PQ-9  
153 molecules loosely bound at the Q<sub>B</sub> site of the D2 protein. After two-electron reduction and  
154 proton uptake, the formed PQH<sub>2</sub> molecule (plastoquinol) dissociates from the Q<sub>B</sub> pocket and  
155 enters the mobile PQ pool in the thylakoid membrane. Re-oxidation of PQH<sub>2</sub> coupled with  
156 proton translocation proceeds at the cytochrome b6/f complex in the so-called Q cycle. PQ-9  
157 is thus involved both in the intersystem electron flow and the establishment of the  
158 transthylakoidal pH gradient. Despite the association of PQ-9, PSII and cytochrome b6/f in  
159 supercomplexes, the oxidation of plastoquinol at the Q<sub>o</sub> site of the cytochrome b6/f  
160 complex is considered to be the slowest step in the linear electron transport chain with a  
161 turnover time of 3.3 to 5 ms [37]. In comparison, upstream electron transports from H<sub>2</sub>O to  
162 PSII centers and from Q<sub>A</sub> to diffusible PQ occur with turnover times in the range 1-2 ms  
163 [38,39]. Downstream transfer from cytochrome b6/f to PSI is significantly faster with half  
164 times of a few hundreds of  $\mu$ s [40].

165

166 In the chloroplasts of vascular plants, PQ-9 is at the crossroad of the linear electron  
167 transport chain with other electron pathways such as the chlororespiratory pathway and the  
168 cyclic electron flow around PSI [41] (Fig. 3). The chlororespiratory chain involves electron  
169 transfer reactions from stromal reductants to oxygen, catalyzed by the NADPH  
170 dehydrogenase complex NDH [42] and a plastid quinol terminal oxidase PTOX [43].  
171 Chlororespiratory electron transport could have a regulatory role by poisoning the redox state  
172 of the PQ-9 pool, which is crucial for various processes including cyclic electron flow,  
173 carotenoid biosynthesis, protein phosphorylation and gene expressions [43]. For instance,  
174 lack of PTOX in the *Arabidopsis immutans* mutant led to a variegated phenotype with white  
175 sectors deprived from photosynthetic pigments [44,45]. This is attributed to a block of  
176 carotenogenesis in the absence of PQ-9 reoxidation by PTOX, resulting in photooxidative  
177 damage [46]. PTOX could also act as a safety valve by preventing overreduction of the PQ-9

178 pool and excessive excitation pressure on PSII [47]. Nevertheless, chlororespiration appears  
179 to be a quantitatively minor process [43], hence limiting its role in photoprotection. In plant  
180 cells, the vast majority of respiratory activity takes places in the mitochondria, segregated  
181 well away from photosynthetic electron transport in the chloroplasts. By contrast, in  
182 cyanobacteria, the thylakoid membranes are the major sites of respiratory electron  
183 transport as well as photosynthesis [48]. The respiratory electron transport chain shares  
184 some components with the photosynthetic electron transport chain including PQ-9 and  
185 cytochrome *b<sub>6</sub>/f*. This gives a role for the respiratory complexes in redox poising, by  
186 donating or removing electrons to prevent excessive oxidation or reduction of the PQ-9 pool.

187  
188 Cyclic electron flow around PSI is a mechanism that recycles electrons from PSI to the PQ  
189 pool. This recycling occurs through two different pathways that transfer electrons from  
190 ferredoxin to PQ-9: one pathway depends on the PROTON GRADIENT REGULATION 5 (PGR5)  
191 and PGR-like 1 (PGRL1) proteins, and the other one depends on the NDH complex [49,50].  
192 Both cyclic pathways have physiological roles in sustaining photosynthesis under fluctuating  
193 light [51]. An important element in this role is to avoid overreduction of the PQ-9 pool and  
194 full reduction of the PSI reaction centers during high light pulses, thus limiting PSI  
195 photodamage.

196  
197 An electron cycle can also occur within PSII via cytochrome *b<sub>559</sub>* and  $\beta$ -carotene [52],  
198 protecting PSII from photodamage under conditions in which the primary electron-donation  
199 pathway leading to water oxidation is inhibited. Under the latter conditions,  
200 cytochrome *b<sub>559</sub>* is preferentially photooxidized. Oxidized cytochrome *b<sub>559</sub>* is then capable of  
201 accepting an electron from a reduced PQ-9 on the electron acceptor side of PSII, thus  
202 forming a cyclic pathway of electron transfer that connects the donor and acceptor sides of  
203 PSII to remove excess oxidizing equivalents (Fig. 3). Since cytochrome *b<sub>559</sub>* is a potential  
204 protector of PSII against photoinhibition [52], reduction of this compound by PQH<sub>2</sub>-9 could  
205 be a component of the photoprotective action of the PQ-9 pool.

206  
207 **PQ Redox State, Signaling and Biosynthesis of Chemical Compounds**  
208 The multiple electron fluxes intersecting at the PQ-9 level (Fig. 3) modulate the redox state  
209 of the PQ-9 pool which appears to play a crucial role in various metabolic regulations. In



210 particular, imbalances in the excitation of the two photosystems are sensed by the PQ-9  
211 pool redox state, giving rise to phosphorylation of the major light-harvesting chlorophyll-  
212 protein complex of PSII (LHCII) [41,53]. Actually, a reduced redox state associated with an  
213 over-excitation of PSII relative to PSI favors the binding of PQH<sub>2</sub> to the Q<sub>o</sub> site of cytochrome  
214 b6/f complex and leads to the activation of a protein kinase, STATE TRANSITION 7 (STN7),  
215 which phosphorylates LHCII [54]. The primary activation of STN7 for LHCII phosphorylation  
216 appears to depend on its interaction with the stromal side of cytochrome b6/f whereas its  
217 inactivation could be controlled by PQH<sub>2</sub>-9 occupancy and turnover at the cytochrome Q<sub>o</sub>  
218 site [55]. The LHCII phosphorylation event causes the migration of the phosphorylated  
219 complex to PSI, thus rebalancing the excitation energy between PSII and PSI in favor of PSI (a  
220 mechanism called 'state 1-state 2 transition'). Oxidation of the PQ-9 pool leads to the  
221 reverse reaction by dephosphorylation of LHCII by a phosphatase (state 2-to-state 1  
222 transition). It is not yet clear whether the phosphatase activity is constitutive or regulated  
223 by PQ. In land plants, the STN7 kinase and the state transitions are important for adaptation  
224 and growth under conditions in which light quality and quantity change frequently [56].

225  
226 Besides state transitions, the redox state of the PQ-9 pool has also been correlated with  
227 changes in gene expressions adjusting the stoichiometry and antenna size of the  
228 photosystems in the longer term [57,58]. For instance, a strongly reduced pool triggers  
229 repression of *Lhcb1* gene expression while an oxidized pool induces expression. This was  
230 shown in experiments where the PQ-9 redox state was modulated by changes in light  
231 intensity or by electron transport inhibitors [57,58]. Although a detailed description of the  
232 molecular events translating the PQ-9 redox state into transcriptomic changes is still  
233 pending, the available data indicate that PQ-9 pool reduction/oxidation levels play an  
234 important regulatory role in balancing excitation energy between the photosystems both by  
235 short-term and long-term mechanisms. The STN7 kinase and its regulation by the PQ redox  
236 state play a key role in both mechanisms [59]. STN7 appears to be positioned at the  
237 beginning of a phosphorylation cascade that communicates the photosynthetic needs to the  
238 chloroplast and nuclear genomes, resulting in the expression regulation of a distinct set of  
239 genes. However, redox regulation of photosynthesis is complex, involving several other  
240 regulators, such as thioredoxin, acting with PQ-9 in a cooperative manner [60].

241

242 Because ROS homeostasis is controlled by STN7, the role of PQ-9 in photosynthetic  
243 acclimation could be indirect through modulation of ROS signaling [61]. A more direct link  
244 with ROS signaling is also possible. Indeed, it is believed that oxygen can be reduced by  
245 plastosemiquinone (PQH<sup>•</sup>, a radical resulting from the reduction of PQ-9 by one electron)  
246 to superoxide and that the latter ROS can be reduced to hydrogen peroxide by PQH<sub>2</sub> [62].  
247 Since hydrogen peroxide is a long-distance signaling molecule playing a role in chloroplast-to-  
248 nucleus communication [63], hydrogen peroxide formation in the PQ pool could participate  
249 in chloroplastic retrograde signaling and changes in photosynthetic gene expression.

250

251 The redox state of the PQ-9 pool is also involved in the biosynthesis of various metabolites.  
252 Phytoene desaturase in the carotenoid biosynthesis pathway requires PQ-9 oxidation by  
253 PTOX [44,45]. The plastoglobular PQ-9 pool is reduced by a type II-dehydrogenase (NDC1)  
254 that was found to be essential for vitamin K biosynthesis [64]. Plastochroman-8 is  
255 synthesized from reduced PQ-9 by VTE1 in the plastoglobules, and this reaction is impaired  
256 when NDC1 is absent and the delivery of reduced PQH<sub>2</sub> is limiting. Synthesis of  
257 plastochroman-8 from PQ is physiologically important because plastochroman-8 exerts  
258 antioxidant activities, particularly in seeds [65]. Incidentally, plastochroman-8 is a long-  
259 chain homolog of  $\alpha$ -tocotrienol (Fig. 1). Recently, oxidized PQ was shown to be required for  
260 the activity of PROTOPORPHYRINOGEN IX OXIDASE as the electron acceptor [66]. This  
261 interaction between PROTOPORPHYRINOGEN IX OXIDASE and the PQ pool is proposed to  
262 function as a feedback loop between photosynthetic electron transport and chlorophyll  
263 biosynthesis.

264

265

### 266 **Antioxidant Functions**

267 PQ-9 and its derivative plastochroman-8 are close to vitamin E (tocopherols and  
268 tocotrienols) both by their chemical structure and their biosynthesis pathway (Figs. 1 and 2).  
269 Another similarity with vitamin E is their potent antioxidant activity. In liposomes, PQ-9, both  
270 in the reduced and oxidized states, and plastochroman-8 inhibit lipid peroxidation with an  
271 efficacy at least as high as that of tocopherols [67]. In fact, PQ-9 possesses a number of  
272 features that are likely to make this compound an excellent antioxidant. First, it is present in

273 high amounts as a diffusible molecule in thylakoids. The concentration of total PQ-9 in  
274 unstressed *Arabidopsis* leaves ( $\sim 600 \text{ ng cm}^{-2}$ , [27]) is noticeably higher than  
275 tocopherol + plastochromanol levels ( $\sim 150 \text{ ng cm}^{-2}$ ). Leaf enrichment in PQ-9 relative to  
276 tocopherols can be even amplified during long-term acclimation of plants to high light  
277 intensities [11,18]. Second, the PQ-9 side chain bears several double bonds contrary to  
278 tocopherols (Fig. 1). Double bonds are known to be preferential targets of  $^1\text{O}_2$  for oxidation  
279 [68], and therefore the unsaturated side-chain of PQ-9 could provide a possibility for PQ-9 to  
280 quench  $^1\text{O}_2$  by a chemical mechanism. Accordingly,  $^1\text{O}_2$  quenching by PQ-9 both in the  
281 reduced and oxidized states was shown *in vitro* in organic solvents [69]. Comparison of PQ  
282 molecules with different lengths of the side chain showed that the  $^1\text{O}_2$  chemical quenching  
283 activity increased with the chain length [7]. Long-chain PQs are more efficient in  $^1\text{O}_2$   
284 scavenging due to higher number of carbons prone to  $^1\text{O}_2$  oxidation. Moreover, the  
285 localization of PQ-9 within the hydrophobic interior of lipidic membranes [70,71] could make  
286 this molecule a better  $^1\text{O}_2$  quencher than  $\alpha$ -tocopherol which is located at the membrane  
287 surface [72]. Nevertheless, antioxidant activity is also provided by the phenolic group of  
288 reduced PQ-9 [73], so that reduced PQ-9 is likely to be a better  $^1\text{O}_2$  quencher than oxidized  
289 PQ-9. In isolated thylakoid membranes, maintenance of the PQ-9 pool in the reduced state  
290 by electron transport inhibitors enhanced the protection against lipid peroxidation and  
291 pigment bleaching [74]. Reduced PQ-9 can also scavenge superoxide and hydrogen peroxide  
292 [75,76]. Third, in thylakoid membranes, photosynthetic electron transport relies on the  
293 interaction between PQ-9 and the PSII reaction centres which are the main  $^1\text{O}_2$  generators  
294 during photosynthesis [77]. It was initially hypothesized that, in the thylakoid membranes,  
295 PQ-9 is located in the fluid bilayer-midplane region allowing rapid lateral movements  
296 between cytochrome b6/f and PSII complexes [78]. However, as mentioned above, more  
297 recent data favor a close compartmentization of PSII, PQ-9, and cytochrome b6/f complex in  
298 membrane microdomains [33,79]. Moreover, PQ-9 diffusion towards/from PSII was recently  
299 proposed to occur via several entries/exits in the PSII reaction centers with an exchange  
300 cavity where PQ-9 can diffuse around [80]. The intimacy and closeness of PQ-9 and PSII are  
301 likely to augment the opportunities for PQ-9 to scavenge  $^1\text{O}_2$  produced in the reaction  
302 centers. Consequently, PQ-9 could constitute a first line of defense against photosynthesis-  
303 produced ROS, supplementing the action of the  $\beta$ -carotene molecules bound to the PSII  
304 centers.

305

306 In *Chlamydomonas reinhardtii*, addition of PQ homologues to cultures grown in the presence  
307 of PQ biosynthesis inhibitors prevented degradation of D1 and the associated  
308 photoinhibition of PSII, confirming the photoprotective role of PQ in microalgae [81]. The  
309 finding that *SPS1* overexpression in *Arabidopsis* concomitantly boosts the PQ-9 biosynthesis  
310 pathway and the plant tolerance to photooxidative stress demonstrates that this class of  
311 molecules does fulfill a protective role *in planta* [18]. Moreover,  $^1\text{O}_2$  concentration was much  
312 lower in the *SPS1*-overexpressing transgenics compared to the wild type [7,27], in line with  
313 the  $^1\text{O}_2$  quenching capacities of PQ-9. This was accompanied by the accumulation of oxidized  
314 forms of PQ-9, such as PQ-C and trihydroxylated PQ-9, as expected if the antioxidative action  
315 of PQ-9 relies on chemical scavenging. Since chemical quenching involves oxidation of the  
316 quencher, PQ-9 is expected to be consumed during its antioxidant activity, as indeed  
317 observed in plants exposed to photooxidative stress conditions [18]. In the *vte1* mutant, the  
318 total PQ-9 levels are constitutively lower than in WT, and this can be attributed to the  
319 chronic oxidation of PQ-9 in the absence of tocopherol [27]. The increased levels of PQ-C in  
320 the *vte1* mutants compared with WT corroborate this interpretation. When *SPS1* is  
321 overexpressed in the *vte1* background, tolerance to photooxidative stress was restored  
322 indicating that PQ-9 can functionally replace tocopherols and plastochromanol-8 (which are  
323 both missing from *vte1* plants) [27]. Increased production of  $^1\text{O}_2$  from the PSII centers in  
324 the *ch1* mutant was associated with an accelerated loss of PQ-9 compared to the wild type  
325 [18], supporting the idea that consumption of PQ-9 in high light results from  $^1\text{O}_2$  oxidation.

326

327 PQ-9 is partially converted to plastochromanol-8 *in planta* [15]. Comparison of the  
328 *arabidopsis vte2* mutant (deficient in tocopherols but containing plastochromanol) and the  
329 *vte1 vte2* double mutant (deficient in both tocopherol and plastochromanol) showed that  
330 plastochromanol-8 plays a crucial antioxidant role for seed survival and early seedling  
331 development [65]. However, adult *vte1 vte2* plants did not exhibit obvious phenotype,  
332 questioning the function of this compound in well-developed plants. The lack of phenotype  
333 could be related to the amounts of pastochromanol found in plant shoots which are modest  
334 compared to PQ-9. Moreover, over-accumulation of plastochromanol-8 is *VTE1*-  
335 overexpressing *Arabidopsis* lines did not result in an increased tolerance to photooxidation  
336 [18]. The exact function of this PQ-9 derivative in plant leaves remains to be clarified.

337

### 338 **The Dynamics of PQ Partitioning Between Thylakoid Membranes and Plastoglobules**

339 When arabidopsis plants were suddenly exposed to high light stress, loss of PQ-9 concerned  
340 principally the thylakoidal pool [27], as expected since the photosystems are the main  
341 source of  $^1\text{O}_2$  in high light. Moreover, PQ-C was detected predominantly in the thylakoid  
342 fractions, confirming that  $^1\text{O}_2$  oxidation of PQ-9 occurs at this level. This is in agreement with  
343 a study by Szymanska and Kruk [15] who showed a selective decrease in the photochemically  
344 active PQ-9 pool in arabidopsis leaves exposed to high light stress. However, a significant  
345 reduction of the total PQ-9 concentration was observed in the photochemically nonactive  
346 pool when the photostress was severe and PQ-9 degradation was very pronounced such as  
347 in the *vte1* background [27]. Therefore, a dynamic exchange of PQ-9 molecules must be  
348 assumed between the thylakoids and their storage sites in the plastoglobules and the  
349 envelopes to compensate the oxidative degradation of PQ-9 molecules during their ROS  
350 scavenging activity in the thylakoid membranes. Accordingly, plastoglobules have been  
351 shown to be physically coupled to thylakoids in a way allowing bidirectional channelling of  
352 lipid metabolites [82,83]. However, experimental data measuring the nature and the rate of  
353 this metabolite exchange are not available. In particular, we do not know if a carrier system  
354 is involved in this exchange. In this context, it is worth mentioning that reduced PQ-9  
355 showed a high mobility in lipid membranes compared with  $\alpha$ -tocopherol [84]. Nevertheless,  
356 the rate of this transfer appeared to be slow compared with the rate of PQ-9 oxidation  
357 under severe high light stress because it could not maintain the pool size of photochemically  
358 active PQs to the control levels measured in low light [27]. Possibly, the protein crowding in  
359 the thylakoid membrane is a limiting factor in the PQ transfer from the plastoglobules to the  
360 lipidic environment of PSII.

361

362 Some progress has been recently made in regards with the control of PQ exchange between  
363 the thylakoid membranes and the plastoglobules. A predicted atypical kinase PROTON  
364 GRADIENT REDUCTION 6 (PGR6, also called ABC1K1) in the plastoglobules was shown to be  
365 required for PQ homeostasis [85]. PGR6 appears to regulate the transfer of PQ-9 molecules  
366 from the plastoglobules to the thylakoid membranes: when the *pgr6* knockout mutant was  
367 transferred to a moderately elevated light intensity, the photoactive PQ-9 pool in the  
368 thylakoid membranes was selectively depleted, reducing photosynthetic efficiency. Another

369 plastoglobular kinase (ABC1K3) has been found to have the opposite effect, limiting PQ-9  
370 availability for electron transport in the thylakoid membranes [86]. The amounts of PQ-9 was  
371 increased in the plastoglobules and decreased in the thylakoids by the *abc1k1 abc1k3*  
372 double mutation [87]. Thus, a complex regulation of PQ distribution within the chloroplast  
373 appears to occur, determining photosynthesis efficiency and tolerance to high light. These  
374 observations suggest that, apart from the absolute concentration of PQ-9, its mobility and  
375 exchange between storage and active pools are critical. The targets of the ABC1K1 and  
376 ABC1K3 kinases are still unknown and remain to be identified.

377  
378 Because PQ-9 somehow functions as a sacrificial antioxidant consumed during oxidative  
379 stress, it must be resynthesized for the pool being refilled. Accordingly, most genes of the  
380 PQ-9 biosynthesis pathway are strongly upregulated during acclimation of Arabidopsis to  
381 high light intensities [18,21]. This induction of PQ-9 biosynthesis genes was accompanied by  
382 a concomitant rise in the size of the total PQ-9 pool, whereas there was less effect on the  
383 tocopherol content [15,18]. However, we cannot exclude metabolization and recycling of  
384 oxidized forms of PQ-9. The plastoglobules are known to contain a repair system allowing  
385 the reconversion of  $\alpha$ -tocopherol quinone to  $\alpha$ -tocopherol [88]. A similar repair system could  
386 exist for PQ-9 considering the presence of oxidoreductases in the plastoglobules, including  
387 NDC1 [64].

388

### 389 **Some Applications of the Antioxidant Properties of PQ**

390 Contrary to ubiquinone [89,90], the antioxidant properties of PQ-9 have not yet been  
391 exploited directly in biotechnological applications, *e.g.* to enhance plant stress tolerance.  
392 However, conjugates of reduced PQ with various cations (SkQ) have been designed to  
393 penetrate mitochondrial cell membranes [91]. Thanks to the antioxidant activity associated  
394 with the plastoquinol part of the molecule, these derivatives can protect animal and human  
395 cells from death from oxidative stress [92] and are effective as anti-aging treatments [93,94].  
396 The development of pharmaceuticals based on SkQ is in progress. In particular, SkQ1 (10-(6-  
397 plastoquinonyl) decyltriphenylphosphonium) can be used for the treatment of dry eye  
398 syndrome, the early stage of cataract and macular degeneration [95]. SkQ1 has also been  
399 applied to plants with some beneficial effects, such as reduced ROS production in the  
400 mitochondria and prevention of cell death [96]. However, treatment of plants with SkQ1 had

401 no effect on ROS produced in the chloroplasts in the light and perturbed photosynthetic  
402 electron transport in the  $\mu\text{M}$  concentration range. Other PQ analogs with antiproliferative  
403 and proapoptotic activities, such as chlorinated PQ and amino benzoquinone, have also been  
404 developed for medical purposes [94, 97].

405

406

#### 407 **Concluding Remarks and Future Perspectives**

408 PQ-9 is a unique component of the photosynthetic machinery with multiple functions in the  
409 operation, regulation and protection of photosynthetic electron transport pathways (Fig. 4).  
410 The dual function of PQ in photosynthesis and photoprotection may stem in the evolution of  
411 photoautotrophic organisms. Quinones are widely distributed in nature, being present in  
412 nearly all living organisms [5]. From an evolutionary perspective, it is interesting to note that  
413 quinonic compounds were detected in interstellar dusts [98], suggesting the involvement of  
414 this type of compounds in early chemical and biological evolutionary steps. Quinones have  
415 also been detected in carbonaceous meteorites, and it has been proposed that such  
416 compounds delivered by meteoritic infall in the prebiotic environment could have played a  
417 role in the development of primitive cellular life [99]. Actually, isoprenoids are amongst the  
418 most ancient organic chemicals which are believed to be necessary constituents in the early  
419 formation of membranes and their evolution [100]. Accordingly, polycyclic aromatic  
420 hydrocarbons such as chrysene quinone were experimentally shown to stabilize and reduce  
421 permeability of a simulated prebiotic membrane [101]. In animal and bacterial cells,  
422 quinonic compounds are present in a variety of membranes supporting physiological roles  
423 other than in respiratory electron transport [102,103], including management of oxidative  
424 stress [104]. Moreover, quinones, and in particular PQ-9, have been shown to affect the  
425 mechanical properties of lipid membranes, increasing membrane stability and changing  
426 permeability [105,106]. The quinone moiety of the molecule appears to be essential for  
427 these effects. In the bacteria *Listeria monocytogenes*, isoprenoid quinone concentration  
428 modulates membrane fluidity as a mechanism for adaptation to low temperature [107]. One  
429 can thus speculate that the PQ ancestor initially played protective and structural roles in  
430 biological membranes which were preserved during evolution and were maintained while  
431 new essential roles were subsequently acquired in electron and proton transport.

432

433 Considering its antioxidative properties, PQ-9 could be a good target for future  
434 developments of plants more tolerant to environmental constraints. A first exemple in this  
435 approach is the successful increase in the stress tolerance of Arabidopsis plants  
436 accumulating PQ-9 by *SPS1* gene overexpression [18]. Possibly, the concomitant  
437 manipulation of other enzymes of PQ-9 biosynthesis could further amplify this effect. On the  
438 other hand, inhibition of the flow of PQ-9 from their storage site in the plastoglobules to the  
439 thylakoid membranes by inactivation of the PGR6 enzymes impaired plant acclimation to  
440 high light intensities [85]. Therefore, improvement of the PQ-9 exchange rate between the  
441 thylakoid membranes and the plastoglobules could constitute another possible way to  
442 improve the acclimation capacities of plants to environmental fluctuations. This will require,  
443 however, a better understanding of the molecular mechanism underlying the partitioning of  
444 PQ-9 within the chloroplast. Because of its multiple functions in the chloroplasts, PQ-9 could  
445 provide an attractive target for improving photosynthesis efficiency and robustness (see  
446 outstanding questions).

447

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454

#### 455 **References**

- 456 1. Cook, W.B. and Miles, D. (1992) Nuclear mutations affecting plastoquinone  
457 accumulation in maize. *Photosynth. Res.* 31, 99-111
- 458 2. Hunter, C.T. et al. (2018) Maize *w3* disrupts *homogentisate solanesyl*  
459 *transferase (ZmHst)* and reveals a plastoquinone-9 independent path for phytoene  
460 desaturation and tocopherol accumulation in kernels. *Plant J.* 93, 799-813.
- 461 3. Sommer, P. and Kofler, M. (1966) Physicochemical properties and methods of analysis  
462 of phylloquinones, menaquinones, ubiquinones, plastoquinones, menadione and  
463 related compounds. In *Vitamins and Hormones Vol. 24*, (Harris, R.S. et al. , eds). pp.  
464 349-400, Academic Press.
- 465 4. Szymańska, R. and Kruk, J. (2018) Novel and rare prenyllipids – Occurrence and  
466 biological activity. *Plant Physiol. Biochem.* 122, 1-9.



- 467 5. Nowicka, B. and Kruk, J. (2010) Occurrence, biosynthesis and function of isoprenoid  
468 quinones. *Biochim. Biophys. Acta.* 1797, 1587-1605.
- 469 6. Szymanska, R. et al. (2014) Hydroxy-plastoquinonol and plastoquinone-C as singlet  
470 oxygen products during photo-oxidative stress in *Arabidopsis*. *Plant Cell Environ.* 37,  
471 1464-1473
- 472 7. Ferretti, U. et al. (2018) Chemical quenching of singlet oxygen by plastoquinols and  
473 their oxidation products in *Arabidopsis*. *Plant J.* 95, 848-861
- 474 8. Dłużewska, J. et al. (2015) New prenyl lipid metabolites identified in *Arabidopsis* during  
475 photo-oxidative stress. *Plant Cell Environ.* 38, 2698-2706.
- 476 9. Kruk, J. et al. (1998) Functions of plastoquinones B and C as electron acceptors in  
477 Photosystem II and fatty acid analysis of plastoquinone B. *Photosynth. Res.* 58, 203-  
478 209.
- 479 10. Liu, M. and Lu, S. (2016) Plastoquinone and ubiquinone in plants: biosynthesis,  
480 physiological function and metabolic engineering. *Front. Plant Sci.* 7, 1898.
- 481 11. Lichtenthaler, H.K. (2007) Biosynthesis, accumulation and emission of carotenoids,  
482 alpha-tocopherol, plastoquinone, and isoprene in leaves under high photosynthetic  
483 irradiance. *Photosynth. Res.* 92, 163-179
- 484 12. DellaPenna, D. and Pogson, B.J. (2006) Vitamin synthesis in plants: tocopherols and  
485 carotenoids. *Annu. Rev. Plant Biol.* 57, 711-738
- 486 13. Moise, A.R. et al. (2014) Mechanistic aspects of carotenoid biosynthesis. *Chem. Rev.*  
487 114, 164–193.
- 488 14. Kim, E.-H. et al. (2015) Fibrillin 5 Is Essential for Plastoquinone-9 Biosynthesis by Binding to  
489 Solanesyl Diphosphate Synthases in *Arabidopsis*. *Plant Cell* 27, 2956-2971
- 490 15. Szymańska, R. and Kruk, J. (2010) Plastoquinol is the main prenyl lipid synthesized  
491 during acclimation to high light conditions in *Arabidopsis* and is converted to  
492 plastochromanol by tocopherol cyclase. *Plant Cell Physiol.* 51, 537-545
- 493 16. Joyard, J. et al. (2009) Chloroplast proteomics and the compartmentation of plastidial  
494 isoprenoid biosynthetic pathways. *Mol. Plant.* 2, 1154-1180
- 495 17. Zbierzak, A.M. et al. (2009). Intersection of the tocopherol and plastoquinol metabolic  
496 pathways at the plastoglobule. *Biochem. J.* 425, 389-399
- 497 18. Ksas, B. et al. (2015) Plant tolerance to excess light energy and photooxidative damage  
498 relies on plastoquinone biosynthesis. *Sci. Rep.* 5, 10919
- 499 19. Grumbach, K.H. and Lichtenthaler, H.K. (1978) Incorporation of  $^{14}\text{CO}_2$  in  
500 prenylquinones in *Chlorella pyrenoidosa*. *Planta* 141, 253-258
- 501 20. Wanke, M. et al. (2000) Half-life of ubiquinone and plastoquinone in spinach cells.  
502 *Plant Sci.* 154, 183-187
- 503 21. Block, A. et al. (2013) Functional modeling identifies paralogous solanesyl-diphosphate  
504 synthases that assemble the side chain of plastoquinone-9 in plastids. *J. Biol. Chem.*  
505 288, 27594-27606.
- 506 22. Kruk, J. and Trebst, A. (2008) Plastoquinol as singlet oxygen scavenger in photosystem  
507 II. *Biochim. Biophys. Acta* 1777, 154-162
- 508 23. Spicher, L. et al. (2016) Lipid antioxidant and galactolipid remodeling under  
509 temperature stress in tomato plants. *Front. Plant Sci.* 7, 167
- 510 24. Gabruk, M. et al. (2016) Natural variation in tocopherols content in *Arabidopsis*  
511 *thaliana* accessions – the effect of temperature and light intensity. *Physiol. Plant.* 157,  
512 147-160

- 513 25. Wise, R.R. (1995) Chilling-enhanced photooxidation: The production, action and study  
514 of reactive oxygen species produced during chilling in the light. *Photosynth. Res.* 45,  
515 79-97
- 516 26. Lichtenthaler, H.K. et al. (1981) Localization of prenylquinones in the envelope of  
517 spinach chloroplasts. *Biochim. Biophys. Acta* 641, 99-105
- 518 27. Ksas, B. et al. (2018) The plastoquinone pool outside the thylakoid membrane serves in  
519 plant photoprotection as a reservoir of singlet oxygen scavengers. *Plant Cell Environ.*  
520 41, 2277-2287.
- 521 28. Yoshida, K. et al. (2010) Simultaneous determination of in vivo plastoquinone and  
522 ubiquinone redox states by HPLC-based analysis. *Plant Cell Physiol.* 51, 836-841.
- 523 29. Forbush, B. and Kok, K. (1968). Reaction between primary and secondary electron  
524 acceptors of photosystem II of photosynthesis. *Biochim. Biophys. Acta* 162, 243–253.
- 525 30. McCauley, S.W. and Melis, A. (1986) Quantitation of plastoquinone photoreduction in  
526 spinach chloroplasts. *Photosynth. Res.* 8, 3-16
- 527 31. Suslichenko, I.S. and Tikhonov, A.N. (2019) Photo-reducible plastoquinone pools in  
528 chloroplasts of *Tradescantia* plants acclimated to high and low light. *FEBS Lett.* 593,  
529 788-798
- 530 32. Kirchhoff, H. (2014) Diffusion of molecules and macromolecules in thylakoid  
531 membranes. *Biochim. Biophys. Acta* 1837, 495-502
- 532 33. Johnson, M.P. et al. (2014) Nanodomains of cytochrome b6f and photosystem II  
533 complexes in spinach grana thylakoid membranes. *Plant Cell* 26, 3051-3061
- 534 34. Gombos, Z. et al. (1998) Lipid saturation induced microviscosity increase has no effect  
535 on the reducibility of flash-oxidized cytochrome f in pea thylakoids. *Plant Physiol.* 86,  
536 335-337
- 537 35. Amesz, J. (1973) The function of plastoquinone in photosynthetic electron transport.  
538 *Biochim. Biophys. Acta* 301, 35–51.
- 539 36. Crane, F. L. (2010). Discovery of plastoquinone: A personal perspective. *Photosynth.*  
540 *Res.* 103, 195–209.
- 541 37. Stiehl, H.H. and Witt, H.T. (1969) Quantitative treatment of the function of  
542 plastoquinone in photosynthesis. *Z. Naturforsch. B* 24, 1588-1598
- 543 38. Rutherford, A.W. (1989) Photosystem II, the water-splitting enzyme. *Trends Biochem.*  
544 *Sci.* 14, 227-232.
- 545 39. Auslander, W. and Junge, W. (1974) The electric generator in the photosynthesis of  
546 green plants. II. Kinetic correlation between protolytic reactions and redox reactions.  
547 *Biochim. Biophys. Acta* 357, 285-298
- 548 40. Haehnel, W. (1984) Photosynthetic electron transport in higher plants. *Annu. Rev.*  
549 *Plant Physiol.* 35, 659-693

- 550 41. Rochaix, J.-D. (2011) Regulation of photosynthetic electron transport. *Biochim.*  
551 *Biophys. Acta* 1807, 375-383
- 552 42. Peltier, G. et al. (2016) NDH-1 and NDH-2 plastoquinone reductases in oxygenic  
553 photosynthesis. *Annu. Rev. Plant Biol.* 67, 55-80.
- 554 43. Nawrocki, W.J. et al. (2015) Functional and molecular characterization of plastid  
555 terminal oxidase from rice (*Oryza sativa*). *Annu. Rev. Plant Biol.* 66, 49-74.
- 556 44. Carol, P. et al. (1999) Mutations in the Arabidopsis gene IMMUTANS cause a  
557 variegated phenotype by inactivating a chloroplast terminal oxidase associated with  
558 phytoene desaturation. *Plant Cell* 11, 57-68.
- 559 45. Wu, D. et al. (1999) The IMMUTANS variegation locus of Arabidopsis defines a  
560 mitochondrial alternative oxidase homolog that functions during early chloroplast  
561 biogenesis. *Plant Cell* 11, 43-55.
- 562 46. Foudree, A. et al. (2012) The mechanism of variegation in immutans provides insight  
563 into chloroplast biogenesis. *Front. Plant Sci.* 3, 260.
- 564 47. Yu, Q. et al. (2014) Functional and molecular characterization of plastid terminal  
565 oxidase from rice (*Oryza sativa*). *Biochim. Biophys. Acta* 1837, 1284-1292.
- 566 48. Mullineaux, C.W. (2014) Co-existence of photosynthetic and respiratory activities in  
567 cyanobacterial thylakoid membranes. *Biochem. Biophys. Acta* 1837, 503-511
- 568 49. Yamori, W. and Shikanai, T. (2016) Physiological functions of cyclic electron transport  
569 around Photosystem I in sustaining photosynthesis and plant growth. *Annu. Rev. Plant*  
570 *Biol.* 67, 81-106
- 571 50. Alric, J. and Johnson, X. (2017) Alternative electron transport pathways in  
572 photosynthesis: a confluence of regulation. *Curr. Opin. Plant Biol.* 37, 78-86
- 573 51. Yamori, W. et al. (2016) A physiological role of cyclic electron transport around  
574 photosystem I in sustaining photosynthesis under fluctuating light in rice. *Sci. Rep.* 6,  
575 20147.
- 576 52. Shinopoulos, K.E. and Brudvig, G.W. (2012) Cytochrome b559 and cyclic electron  
577 transfer within photosystem II. *Biochim. Biophys. Acta* 1817, 66-75
- 578 53. Minagawa, J. (2011) State transitions—The molecular remodeling of photosynthetic  
579 supercomplexes that controls energy flow in the chloroplast. *Biochim. Biophys. Acta*  
580 1807, 897-705
- 581 54. Shapiguzov, A. et al. (2016) Activation of the Stt7/STN7 kinase through dynamic  
582 interactions with the cytochrome b6f complex. *Plant Physiol.* 171, 82-92
- 583 55. Dumas, L. et al. (2017) A stromal region of cytochrome b6f subunit IV is involved in the  
584 activation of the Stt7 kinase in *Chlamydomonas*. *Proc. Natl. Acad. Sci. USA* 114, 12063-  
585 12068
- 586 56. Bellafiore, S. et al. (2005) State transitions and light adaptation require chloroplast  
587 thylakoid protein kinase STN7. *Nature* 433, 892-895.
- 588 57. Escoubas, J.M. et al. (1995) Light intensity regulation of cab gene transcription is  
589 signaled by the redox state of the plastoquinone pool. *Proc. Natl. Acad. Sci. USA* 92,  
590 10237-10241
- 591 58. Allen, J.F. et al. (2011) Discrete redox signaling pathways regulate photosynthetic light-  
592 harvesting and chloroplast gene transcription. *PLoS One* 6, e26372
- 593 59. Pesaresi, P. et al. (2009) Arabidopsis STN7 kinase provides a link between short- and  
594 long-term photosynthetic acclimation. *Plant Cell* 21, 2402-2423

- 595 60. Bräutigam, K., Dietzel, L. and Pfannschmidt, T. (2010) Hypothesis: A  
596 binary redox control mode as universal regulator of photosynthetic light acclimation.  
597 Plant Signal. Behav. 5, 81-85
- 598 61. Tikkanen, M. et al. (2012) STN7 operates in retrograde signaling through  
599 controlling redox balance in the electron transfer chain. Front. Plant Sci. 3, 277.
- 600 62. Mubarakshina, M.M. and Ivanov, B.N. (2010) The production and scavenging of  
601 reactive oxygen species in the plastoquinone pool of chloroplast thylakoid membranes.  
602 Physiol. Plant. 140, 103-110
- 603 63. Exposito-Rodriguez, M. et al. (2017) Photosynthesis-dependent H<sub>2</sub>O<sub>2</sub> transfer from  
604 chloroplasts to nuclei provides a high-light signalling mechanism. Nat. Commun. 8, 49.
- 605 64. Eugeni Piller, L. et al. (2011) Chloroplast lipid droplet type II NAD(P)H quinone  
606 oxidoreductase is essential for prenylquinone metabolism and vitamin K1  
607 accumulation. Proc. Natl. Acad. Sci. USA 108, 14354-14359.
- 608 65. Mène-Saffrané, L. et al. (2010) Plastochromanol-8 and tocopherols are essential lipid  
609 soluble antioxidants during seed desiccation and quiescence in *Arabidopsis*. Proc. Natl.  
610 Acad. Sci. USA. 107, 17815–17820
- 611 66. Brzewowski, P. et al. (2019) The function of PROTOPORPHYRINOGEN IX OXIDASE in  
612 chlorophyll biosynthesis requires oxidised plastoquinone in *Chlamydomonas*  
613 *reinhardtii*. Commun. Biol. 2,159
- 614 67. Nowicka, B. et al. (2013) Function of plastochromanol and other biological prenyllipids  
615 in the inhibition of lipid peroxidation – A comparative study in model systems.  
616 Biochim. Biophys. Acta 1828, 233-240
- 617 68. Triantaphylidès, C. and Havaux, M. (2009) Singlet oxygen in plants: production,  
618 detoxification and signaling. Trends Plant Sci. 14, 219-228.
- 619 69. Gruszka, J. et al. (2008) Tocochromanols, plastoquinols, and other biological  
620 prenyllipids as singlet oxygen quenchers – determination of singlet oxygen quenching  
621 rate constants and oxidation products. Free Rad. Biol. Med. 45, 920-928
- 622 70. Kruk, J. (1988) Physicochemical properties of charge-transfer complexes of  
623 plastoquinone and alpha-tocopherol quinone, and their possible role in vivo. Biophys.  
624 Chem. 32, 51-56.
- 625 71. Kruk, J. et al. (1993) Fluorescence properties of plastoquinol, ubiquinol and alpha-  
626 tocopherol quinol in solution and liposome membranes. J. Photochem. Photobiol.  
627 B. 19, 33-38
- 628 72. Kruk, J. et al. (2006) Fluorescence lifetimes study of alpha-tocopherol and biological  
629 prenylquinols in organic solvents and model membranes. Photochem. Photobiol. 82,  
630 1309-1314.
- 631 73. Stasiuk, M. and Kozubek, A. (2010) Biological activity of phenolic lipids. Cell. Mol. Life  
632 Sci. 67, 841-860
- 633 74. Hundal, T. et al. (1995) Antioxidant activity of reduced plastoquinone in chloroplast  
634 thylakoid membranes. Arch. Biochem. Biophys. 324, 117-122.
- 635 75. Kruk, J. et al. (2003) Scavenging of superoxide generated in photosystem I by  
636 plastoquinol and other prenyllipids in thylakoid membranes. Biochemistry 42, 8501-  
637 8505.
- 638 76. Khorobrykh, S. and Tyystjärvi, E. (2018) Plastoquinol generates and scavenges reactive  
639 oxygen species in organic solvent: Potential relevance for thylakoids. Biochim.  
640 Biophys. Acta 1859, 1119-1131

- 641 77. Krieger-Liszkay, A. et al. (2008) Singlet oxygen production in photosystem II and related  
642 protection mechanism. *Photosynth. Res.* 98, 551-564.
- 643 78. Millner, P.A. and Barber, J. (1984) Plastoquinone as a mobile redox carrier in the  
644 photosynthetic membrane. *FEBS Lett.* 169, 1-6
- 645 79. Lavergne, J. and Joliot, P. (1991) Restricted diffusion in photosynthetic membranes.  
646 *Trends Biochem. Sci.* 16, 129–134
- 647 80. Van Eerden, F.J. et al. (2017) Exchange pathways of plastoquinone and plastoquinol in  
648 the photosystem II complex. *Nature Comm.* 8, 15214
- 649 81. Trebst A. et al. (2004) Reversal of the inhibition of photosynthesis by herbicides  
650 affecting hydroxyphenylpyruvate dioxygenase by plastoquinone and tocopheryl  
651 derivatives in *Chlamydomonas reinhardtii*. *Pest Manag. Sci.* 60, 669-674.
- 652 82. Austin, J.R. 2nd et al. (2006) Plastoglobules are lipoprotein subcompartments of the  
653 chloroplast that are permanently coupled to thylakoid membranes and contain  
654 biosynthetic enzymes. *Plant Cell* 18, 1693-1703
- 655 83. Bréhélin, C. and Kessler, F. (2008) The plastoglobule: a bag full of lipid biochemistry  
656 tricks. *Photochem. Photobiol.* 84, 1388-1394.
- 657 84. Jemioła-Rzemińska, M. et al. (2003) Anisotropy measurements of intrinsic fluorescence  
658 of prenyllipids reveal much higher mobility of plastoquinol than alpha-tocopherol in  
659 model membranes. *Chem. Phys. Lipids.* 123, 233-243.
- 660 85. Pralon, T. et al. (2019) Plastoquinone homeostasis by *Arabidopsis* proton gradient  
661 regulation 6 is essential for photosynthetic efficiency. *Commun. Biol.* 2,220.
- 662 86. Pralon, T. et al. (2020) Mutation of the atypical kinase ABC1K3 partially rescues the  
663 PROTON GRADIENT REGULATION 6 phenotype in *Arabidopsis thaliana*. *Front Plant Sci.*  
664 11, 337.
- 665 87. Lundquist, P.K. et al. (2013) Loss of plastoglobule kinases ABC1K1 and ABC1K3 causes  
666 conditional degreening, modified prenyl-lipids, and recruitment of the jasmonic acid  
667 pathway. *Plant Cell* 25, 1818-1839
- 668 88. Spicher, L. and Kessler, F. (2015) Unexpected roles of plastoglobules (plastid lipid  
669 droplets) in vitamin K1 and E metabolism. *Curr. Opin. Plant Biol.* 25, 123-129.
- 670 89. Ayer, A. et al. (2015) CoQ<sub>10</sub> function and role in heart failure and ischemic heart  
671 disease. *Annu. Rev. Nutr.* 35, 175-213
- 672 90. Mantle, D. and Hargreaves, I. (2019) Coenzyme Q10 and degenerative disorders  
673 affecting longevity: an overview. *Antioxidants* 8, 44
- 674 91. Skulachev, V.P. (2013) Cationic antioxidants as a powerful tool against mitochondrial  
675 oxidative stress. *Biochim. Biophys. Res. Comm.* 441, 275-279
- 676 92. Zernii, E.Y. et al. (2018) Mitochondria-targeted antioxidant SKQ1 protects cornea from  
677 oxidative damage induced by ultraviolet irradiation and mechanical injury. *BMC*  
678 *Ophthalmology* 18, 336

- 679 93. Shabalina, I.G. et al. (2017) Improved health-span and lifespan in mtDNA mutator mice  
680 treated with the mitochondrially targeted antioxidant SkQ1. *Aging* 9, 315-339.
- 681 94. Ciftci, H.I. et al. (2019) Discovery and structure-activity relationship  
682 of plastoquinone analogs as anticancer agents against chronic myelogenous leukemia  
683 cells. *Arch. Pharm.* 352:e1900170.
- 684 95. Muraleva, N.A. et al. (2019) Suppression of AMD-like pathology by mitochondria-  
685 targeted antioxidant SkQ1 is associated with a decrease in the accumulation of  
686 Amyloid  $\beta$  and in mTOR activity. *Antioxidants (Basel)* 8, 177
- 687 96. Samuilov, V.D. et al. (2019) Mitochondria-targeted quinones suppress the generation of  
688 reactive oxygen species, programmed cell death and senescence in plants.  
689 *Mitochondrion* 46, 164-171
- 690 97. Bayrak, N. et al. (2019) Design, synthesis, and biological activity  
691 of Plastoquinone analogs as a new class of anticancer agents. *Bioorg. Chem.* 92,  
692 103255.
- 693 98. Krueger, F.R. et al. (2004) Assignment of quinone derivatives as the main compound  
694 class composing 'interstellar' grains based on both polarity ions detected by the  
695 'Cometary and Interstellar Dust Analyser' (CIDA) onboard the spacecraft STARDUST.  
696 *Rapid Comm. Mass Spectrom.* 18, 103-111
- 697 99. Milshteyn, D. et al. (2019) Chemiosmotic energy for primitive cellular life: Proton  
698 gradients are generated across lipid membranes by redox reactions coupled to  
699 meteoritic quinones. *Sci. Rep.* 9, 12447
- 700 100. Ourisson, G. and Nakatani, Y. (1994) The terpenoid theory of the origin of cellular life:  
701 the evolution of terpenoids to cholesterol. *Chem. Biol.* 1, 11-23
- 702 101. Groen, J. et al. (2012) Polycyclic aromatic hydrocarbons as plausible prebiotic  
703 membrane components. *Orig. Life. Evol. Biosph.* 42, 295-306
- 704 102. Bentinger, M. et al. (2007) The antioxidant role of coenzyme Q. *Mitochondrion* 7S, S41-  
705 S50.
- 706 103. Gille, L. et al. (2008) Ubiquinone and tocopherol: dissimilar siblings. *Biochem.*  
707 *Pharmacol.* 76, 289-302
- 708 104. Soballe, B. and Poole, R.K. (1999) Microbial ubiquinones: multiple roles in respiration,  
709 gene regulation and oxidative stress management. *Microbiology* 145, 1817-1830
- 710 105. Hernandez, V.A. et al. (2015) Ubiquinone-10 alters mechanical properties and  
711 increases stability of phospholipid membranes. *Biochim. Biophys. Acta* 1848, 2233-  
712 2243
- 713 106. Skowronek, M. et al. (1996) Influence of the redox state of ubiquinones and  
714 plastoquinones on the order of lipid bilayers studied by fluorescence anisotropy of  
715 diphenylhexatriene and trimethylammonium diphenylhexatriene. *Biochim. Biophys.*  
716 *Acta* 1280,115-119.
- 717 107. Seel, W. et al. (2018) Increased isoprenoid quinone concentration modulates  
718 membrane fluidity in *Listeria monocytogenes* at low growth temperatures. *J. Bacteriol.*  
719 200, e00148-18.

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729 Figure legends

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731 Figure 1. Chemical structure of plastoquinone-9, plastochromanol-8,  $\alpha$ -tocopherol and  $\alpha$ -  
732 tocotrienol.

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734 Figure 2. Biosynthesis pathways of plastoquinone (in red), plastochromanol-8 (in black) and  
735 vitamin E ( $\alpha$ -tocopherol (in green) and  $\alpha$ -tocotrienol (in blue)) in plants.

736 Metabolites: DP, diphosphate; HGA, homogentisate; GGDP, geranylgeranyl disphosphate,  
737 HPP, hydroxyphenylpyruvate; IPP, isopentenyl-pyrophosphate; MSBQ, 2,3-dimethyl-6-  
738 solanesyl-1,4-benzoquinol; MPBQ, 2-methyl-6-phytyl-1, 4-benzoquinol; DMPBQ, 2,3-  
739 dimethyl-6-phytyl-1,4-benzoquinone; MGGBQ, 2-methyl-6- geranylgeranyl Benzoquinone;  
740 DMGGBQ, 2,3-dimethyl-6-geranylgeranyl benzoquinone.

741 Enzymes: HST, homogentisate solanesyl transferase; HPT, homogentisate phytyl transferase;  
742 VTE1, tocopherol cyclase; VTE3, phytylbenzoquinol methyltransferase; VTE4,  $\gamma$ -tocopherol  
743 methyltransferase; HGGT, homogentisate geranylgeranyl transferase; HPPD,  
744 hydroxyphenylpyruvate dioxygenase; SPS, solanesyl diphosphate synthase.

745

746 Figure 3. Schematic representation of the photosynthetic electron flows intersecting at the  
747 PQ-9 pool: linear electron flow (in black), cyclic electron flow around PSI (in blue), cyclic  
748 electron flow around PSII (in green) and chlororespiration (in red). b559, cytochrome b559;  
749 Fd, ferredoxin; PC, plastocyanin.

750

751 Figure 4. Scheme illustrating functions of PQ-9 in plants modulated by the dynamic  
752 partitioning of the PQ-9 molecules between the photochemically active pool in the thylakoid  
753 membranes and the photochemically non-active pool stored in the plastoglobules.









