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REVIEW

# Production of carotenoids by microalgae: achievements and challenges

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**Abstract** Carotenoids are a wide group of lipophylic isoprenoids synthesized by all photosynthetic organisms and also by some non-photosynthetic bacteria and fungi. Animals, which cannot synthesize carotenoids de novo, must include them in their diet to fulfil essential provitamin, antioxidant, or colouring requirements. Carotenoids are indispensable in light harvesting and energy transfer during photosynthesis and in the protection of the photosynthetic apparatus against photooxidative damage. In this review, we outline the factors inducing carotenoid accumulation in microalgae, the knowledge acquired on the metabolic pathways responsible for their biosynthesis, and the recent achievements in the genetic engineering of this pathway. Despite the considerable progress achieved in understanding and engineering algal carotenogenesis, many aspects remain to be elucidated. The increasing number of sequenced microalgal genomes and the data generated by high-throughput technologies will enable a better understanding of carotenoid biosynthesis in microalgae. Moreover, the growing number of industrial microalgal species genetically modified will allow the production of novel strains with enhanced carotenoid contents.

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## Introduction

Carotenoids are the most diverse and widespread pigments found in nature (Sasso et al. 2012). They are a wide group of lipophylic isoprenoids synthesized by all photosynthetic organisms and also by some non-photosynthetic bacteria and fungi. The central $C_{40}$ backbone, made up of eight isoprene units, forms a polyene chain of conjugated double bonds and establishes an extended π-electron system that accounts for its ability to absorb both ultraviolet (UV) radiation and visible light (Grossman et al. 2004). The number of conjugated double bonds within this basic backbone, as well as cyclic and oxygenic modifications, yields a variety of carotenoids whose colours range from yellow to reddish brown. More than 750 carotenoid structures have been isolated from different natural sources (Britton et al. 2004). These carotenoids and the pathways involved in their biosynthesis are frequently used as taxonomic markers within the diverse microalgal phyla (Takaichi 2011). Despite the wide diversity of carotenoids structures, no more than 30 of them play a direct role in photosynthesis of eukaryotic microalgae.

Carotenoids are indispensable in light harvesting and energy transfer during photosynthesis and in the protection of the photosynthetic apparatus against photooxidative damage (Li et al. 2009). Most carotenoids are bound to integral membrane proteins, associated with light-harvesting complexes (LHCs), where they absorb light across a broader range of the spectral region and transfer the energy to chlorophyll, initiating the photochemical events of