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Review

Fungal and yeast carotenoids

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This review reports and discusses all available information about the fungal carotenoids such general characters, derivatives, common names, chemical structure, molecular formula, color, bioactivity, and industrial applications in medicine, pharmacology, food processing, cosmetics, dyeing and others. It also reviews the classification of the fungal carotenoids, biosynthetic pathway, distribution and function inside the fungal cells. Approximately, 34 fungal carotenoids derivatives are widely distributed in fungal genera species and fungal groups. Fermented carotenoids produce by fungi from agro-industrial wastes have many advantages and solve the production problems. Development of the fungal carotenoids productivity is reported by two main strategies such as metabolic and genetic engineering.

Key words: Fungal carotenoids, natural pigment, applications, bioactivity.

INTRODUCTION

Science civilization human tried to find the natural source of pigments for coloring their foods, clothes, and everything. Overpopulation around the world required development in the coloring industry and expansion in using the synthetic pigments which causes numerous problems considerably environmental pollution with toxic adverse effect on humans and causes very dangerous diseases. The industrialists and health professionals seek to find safe natural food colorants such as natural carotenoids.

Fungal carotenoids have many advantages as they are natural safe pigment, visually wonderful appealing colors, probiotic, beneficial to health with high (antioxidant, nutritional value, yields) and stabile against (light, radiation, heat and pH), good quality, low costs, environmental friendly, weather independent, consumed few days, easily extracted and separated from the growth media (Joshi et al., 2003; Nagpal et al., 2011; Aberoumand, 2011; Ahmad et al., 2012, 2014; Malik et al., 2012).

Fungal carotenoids have numerous applications on industrial scales such folk and modern medicine, pharmacology, nutritional food colorants in many food industries, cosmetics and perfume, dyeing, supplementary foods and feeds, chemotaxonomic classifications and diagnostic markers. In 2010, carotenoids market was estimated at nearly $1.2 billion but in 2018 they increased considerably to $1.4 billion with a compound annual growth rate of 2.3%. Also, Astaxanthin is the third most important carotenoid economically after β-carotene and lutein. Astaxanthin market reached the 29% of total carotenoid sales with a global market size of $225 million dollars, estimation increased to $253 million by 2018, approximately (Nagpal et al., 2011; Malik et al., 2012).

Carotenoids are diterpenoids derived from the ACO metabolic pathway. They are synthesized in cytoplasm and stored in cytoplasmic vesicles (lipid globules) and transported to be associated with the fungal plasma membrane fraction as structural and functional molecules.

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Carotenoids have very important functions in the fungal cells; they act as antioxidant against free radical, protective molecules or photoreceptors against lethal or strong light intensity and radiations, and maintain membrane stability and fluidity. They also act as a source of the sex hormones for completing the fungal life cycle (Turner, 1971; Goodwin, 1976; Grifin, 1994; Sahadevan et al., 2013; Erasun and Johnson, 2018).

Natural carotenoids are classified into two large groups including non-oxygenated carotenoids derivatives have C_{40} and xanthophylls have C_{40} or oxygenated carotenoids. They are very active molecules that act as precursors of the vitamin A, antioxidant properties, protective molecules for preventing and treating numerous dangerous human diseases. They have wide diversity in different fungal groups, genera and species reviewed by many researchers (Johnson and Schroeder, 1995; Sardaryan et al., 2004; Malik et al., 2012; Venil et al., 2013; Kirti et al., 2014; Mata-Gómez et al., 2014; Tuli et al., 2015; Erasun and Johnson, 2018).

Production of fungal carotenoids by fermentation is promising for industrial development through metabolic engineering by controlling the nutritional and environmental growth factors (Mata-Gómez et al., 2014).

Metabolic engineering is the best strategy to increase the fungal and yeast carotenoids productivity and reduce the production cost by the selection of hyper-producer strains and development of their nutritional and environmental factors. Also, different extraction techniques affect the production of carotenoids amount (Yamano et al., 1994; Shimada et al., 1998; Mata-Gómez et al., 2014).

More recently many authors tested the development of the yeast carotenoids productivity by genetic engineering by selecting the non carotenogesis yeast *Saccharomyces cerevisiae, Candida utilis* (Miura et al., 1998) and *Pichia pastoris* (Araya-Garay et al., 2012). Genetic engineering promises the world more development and increases yeast carotenoids productivity to face the industrial needs (Mata-Gómez et al., 2014, Wang et al 2017).

This review has been designed to focus on the fungal carotenoids, physical and chemical characters, biosynthetic pathway, classifications and their derivatives, function, importance and distribution inside the fungal cells, bioactivity for prevention and treatments of many human and animal diseases, economic importance and industrial applications as well as advantages of carotenoids production by fungal and yeast fermentation and strategies for development of the carotenoids productivity on industrial scales for facing the world needs.

INDUSTRIAL APPLICATIONS AND ECONOMIC IMPORTANCE OF THE FUNGAL CAROTENOIDS

Natural carotenoids take a high rank and preferred on large industrial scales and accelerating with consumers. Carotenoids are desired for natural colorants for industrial applications in chemical, folk and modern medicine, pharmacology, nutritional food colorants in cakes, confectionaries, candies, pudding, jelly, fruits, decoration of food, baby foods, breakfast cereals, pasta, sauces, processed cheese, fruit, vitamin-enriched milk products, energy drinks and beverages, cosmetics and perfume, dyeing of wood, texture, leather, papers and painting, and supplementary foods and feed used to prevent numerous human diseases and protect human health, also used in fungal chemotaxonomic classifications and diagnostic markers (Rodríguez-Sáiz et al., 2010; Nagpal et al., 2011; Malik et al., 2012; Moharram et al., 2012; Eman, 2015, 2016; Narsing-Rao et al., 2017; Meléndez-Martínez et al., 2019; Ramesh et al., 2019; Zhao et al., 2019) (Table 1).

FUNGAL CAROTENOIDS BIOACTIVITY

Table 1 summarizes the carotenoids bioactivity reported by many authors such as precursors of vitamin A, antioxidant, protective molecules for preventing and treating numerous dangerous human diseases such as prevention of photo-aging, anti-skin sun burning, anti-lung cancer and antitumor, anticholesterol and anti-cardiovascular diseases, degeneration and cataract antiparasitic, immune enhancer, antiparasitic, antimicrobial, antiinflammatory, erythropoietic, protoporphyria and providing major benefits to health (Malik et al., 2012; Venil et al., 2013; Mata-Gómez et al., 2014; Tuli et al., 2015; Eman and Abbady, 2014; Eman and Farghaly, 2014; Farghaly and Eman, 2015; Eman et al., 2018; Tan and Norhaizan, 2019; Ramesh et al., 2019).

GENERAL CHARACTERS AND ADVANTAGES OF THE FUNGAL CAROTENOIDS

Fungal carotenoids are natural safe pigment with many advantages including visually wonderful appealing colors such as probiotic health benefits with highly nutritional value, high yields and high stability, good quality, low costs, and needed few nutritional and environmental requirements from agro-industrials wastes, environmentally friendly, weather independent, consumed few days, easily extracted and separated from the growth media (Joshi et al., 2003; Nagpal et al., 2011; Malik et al., 2012; Wang et al., 2017; Zhao et al., 2019).

Fungal carotenoids classification

Approximately, 700 to 800 derivatives compounds related to natural carotenoids are classified into two large groups including non-oxygenated polyunsaturated hydrocarbons

Table 1. Industrial applications of the fungal carotenoids and bioactivity.

Industrial applications and bioactivity	Fungal carotenoids							
	β-Carotene	**Ƴ-Carotene**	**Lycopene**	**Phytofluene**	**Torulene**	**Lycoperesne**	**Antheraxanthin**	**Torularhodin**
Natural food colorant	+		+		+	+	+	+
Animal feed	+				+			+
Vitamin A precursor	+	+						
Photoreceptor	+							
Help absorption of vitamin E (α-tocopherol)	+							
Skin protective	+		+	+			+	
Cosmetic					+			+
Prevent blindness								
Pharmaceutical			+		+			
Antioxidant		+		+		+		+
Immunomodulatory					+			
Anticancer	+							
Antiparasitic								+
Antiaging cataract	+							
Anti-cholesterol	+							
Antiheart diseases			+					
Anti-inflammatory				+				
Antimicrobial					+	+		+
Dyeing (textiles)	+							
Source of plant hormone abscisic acid	+							

Industrial applications and bioactivity	Fungal carotenoids							
	Astaxanthin	**Canthaxanthin**	**Lutein**	**Flavoxanthin**	**Cryptoxanthin**	**Neoxanthin**	**Violaxanthin**	**Zeaxanthin**
Natural food colorant	+		+	+	+		+	+
Animal feed	+		+					+
Vitamin A precursor		+			+			
Photoreceptor								
Help absorption of vitamin E (α-tocopherol)								
Skin protective								+
Cosmetic	+	+				+	+	
Prevent blindness								
Pharmaceutical		+	+				+	
Antioxidant					+		+	
Immunomodulatory							+	
Anticancer					+		+	

Table 1. Contd.

Antiparasitic		+	
Antiaging cataract			
Anti-cholesterol			+
Antiheart diseases			
Anti-inflammatory			
Antimicrobial			
Dyeing (textiles)		+	
Source of plant hormone abscisic acid	+		

carotenes derivatives having C_{40} and xanthophyll having C_{40} with oxygen or oxygenated carotenoids (Table 5). Thirty four fungal carotenoids derivatives are produced by fungi and included fourteen carotenes and twenty xanthophyll derivatives reported in this review (Davies, 1976; Malik et al., 2012; Venil et al., 2013; Kirti et al., 2014; Mata-Gómez et al., 2014; Tuli et al., 2015; Kuczynska and Jemiola-Rzeminska, 2017; Manik et al., 2017; Erasun and Johnson, 2018) (Table 5).

Mevalonate biosynthetic pathway in fungi

Erasun and Johnson (2018) reported that numerous and very important secondary metabolites are synthesize from mevalonate biosynthetic pathway. Carotenoids act as a source of four large groups of compounds (Figure 1) including:

(1) Vitamin A or retinoid compounds C_{20} include retinal, retinoic acid and retinol.
(2) Apo-carotenoids $C_{<40}$ include abscisic acid, apocarotenal, bixin, crocetin, food orange 7 color, ionones and peridinin.
(3) Higher carotenoids and xanthophyll.
(4) Also, these pathways synthesize many important vitamins.

Fungal carotenoids biosynthetic pathway in details

Many authors reported the metabolic pathway of carotenoids biosynthesis by yeasts (Goodwin, 1976; Turner, 1971; Czeczuga, 1979; Vachali et al., 2012; Venil et al., 2013; Mata-Gómez et al., 2014; Kiokias et al., 2016) (Figures 1 and 2) summarized in the following:
(1) Acetyl CoA is converted to 3-hidroxy-3-methyl-glutaryl-CoA (HMG-CoA) and catalyzed by HMG-CoA synthase enzyme.
(2) Then, HMG-CoA is converted in mevalonic acid (MVA), this is the first precursor of terpenoids biosynthetic pathway.
(3) MVA is phosphorylated by MVA kinase and decarboxylation into isopentenyl pyrophosphate IPP.
(4) IPP is isomerized to dimethyllayl pyrophosphate (DMAPP) with the addition of three IPP molecules to DMAPP, catalyzed by prenyl-transferase into geranyl geranyl pyrophosphate (GGPP).
(5) Condensation of two molecules of GGPP produces the phytoene (the first C_{40} carotene of the pathway) and converted to ζ-Carotene.
(6) ζ-Carotene is converted to neurosporene.
(7) Neurosporene is subsequently desaturated to form lycopene.
(8) Many cyclic carotenoids are derived from lycopene.
(9) Neurosporene and lycopene act as a procurer of numerous derivatives of carotenoids as shown in Figures 1 and 2.

Distribution and function of carotenoids inside the fungal cells

Fungal carotenoids are synthesized in cytoplasm, stored in cytoplasmic vesicles (lipid globules) and transported to be associated with the fungal plasma membrane fraction as structural and functional molecules. Carotenoids have very important functions in the fungal cells; they act as antioxidant against free radical, protective molecules or photoreceptors against lethal or strong light intensity and radiations, and maintain membrane stability and fluidity (Figure 3). They also act as a source of the sex hormones for completing the fungal life cycle (Sahadevan et al., 2013;

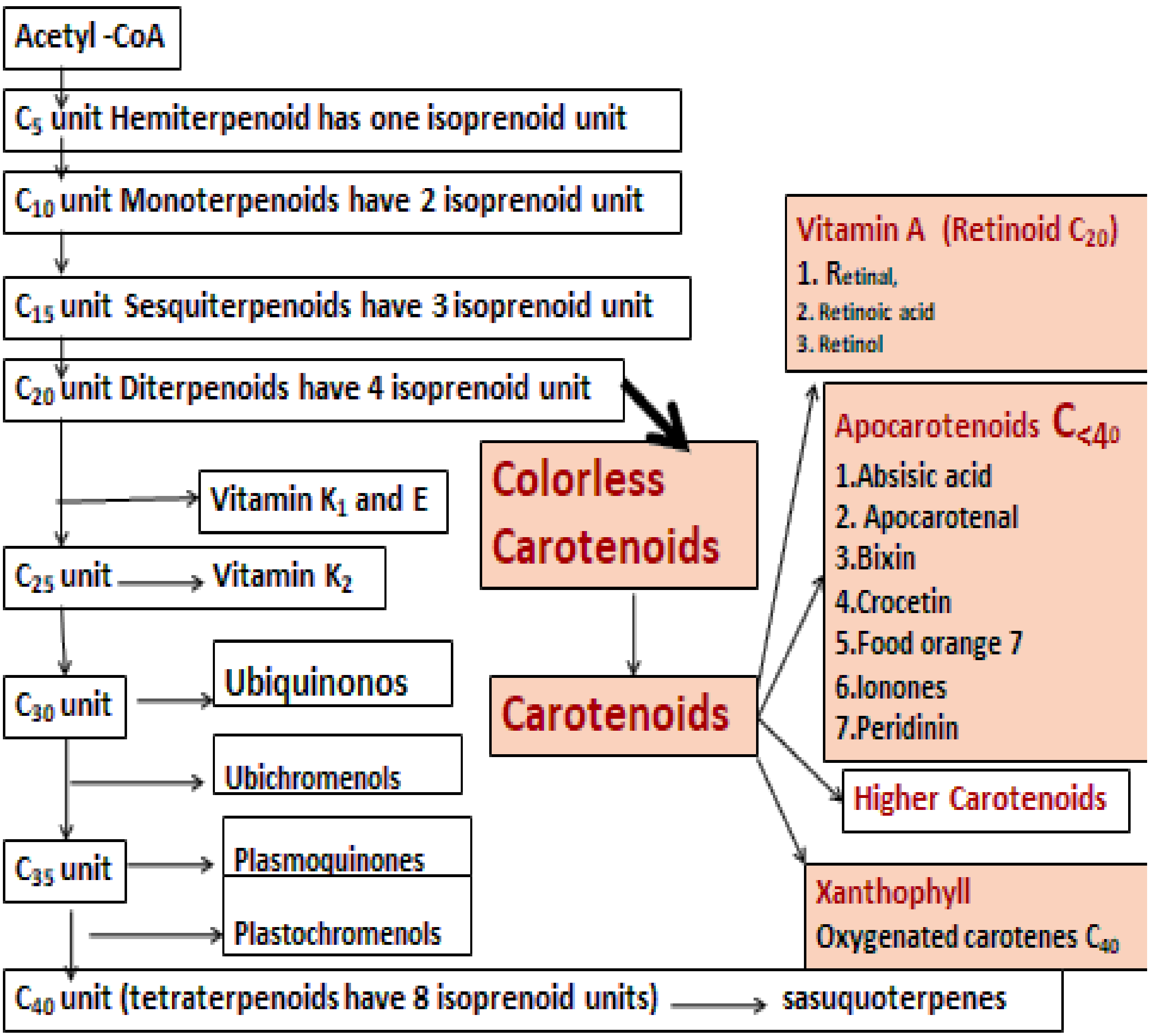


Figure 1. Mevalonate biosynthetic pathways for synthesis of carotenoids and other products (Erasun and Johnson 2018) and modified by this review.

Erasun and Johnson, 2018).

They also act as a source of the sex hormones for completing the fungal life cycle (Turner, 1971; Goodwin, 1976; Grifin, 1994; Sahadevan et al., 2013; Erasun and Johnson, 2018).

Sahadevan et al. (2013) reported the β-carotene in *Blakeslea trispora* and *Mucor mucedo*. Zygomycetes act as a source of the male and female sex hormones for help to meet and contact between male and female gametes for completing the sexual reproduction and completing the fungal life cycle (Figure 4).

Biodiversity of carotenoids in fungal genera and species

Carotenoids have wide range of distribution in all fungal groups reviewing and reporting approximately 70 species related to 40 genera from all the fungal groups (Andrewes et al., 1976; Andrewes and Starr, 1976; Davies, 1976; Johnson and Schroeder, 1995; Domínguez-Bocanegra et al., 2007; Yurkov et al., 2008; Barredo, 2012; Malik et al., 2012; Venil et al., 2013; Mata-Gómez et al., 2014; Tuli et al., 2015; Manimala and

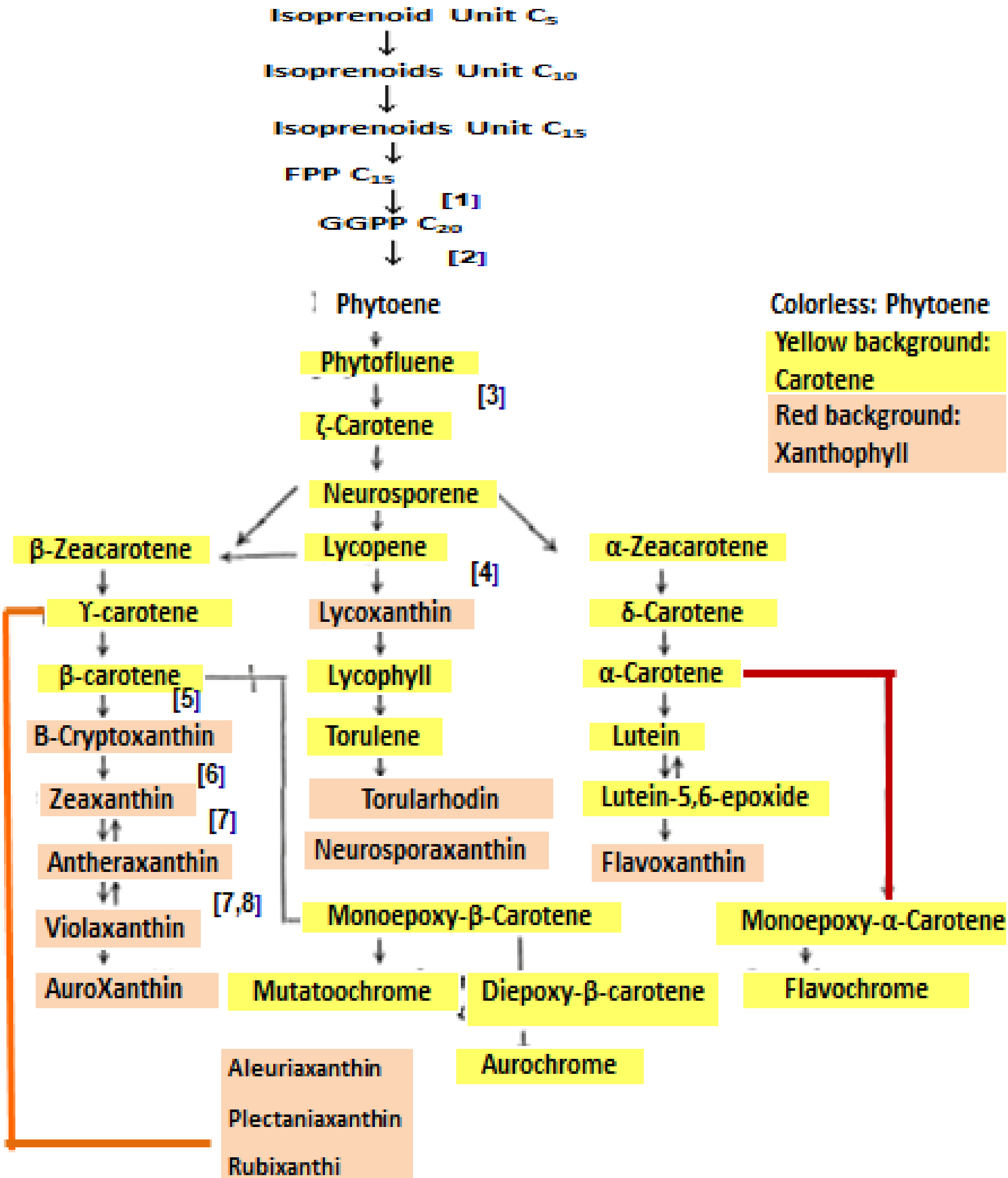


Figure 2. Details discussing the biosynthesis of different carotenoids derivatives in Helvellaceae and Morchellaceae and other fungi (Andrewes et al., 1976; Andrewes and Starr 1976; Czeczuga, 1979; Erasun and Johnson, 2018) and modified by this review.

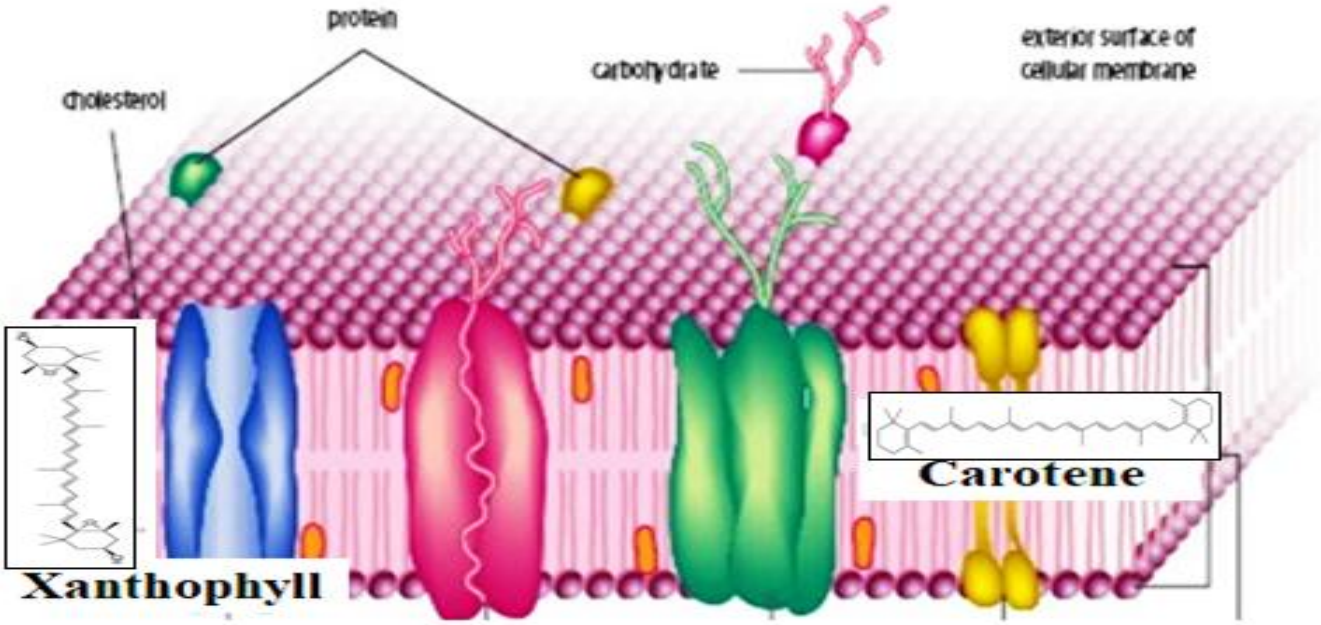


Figure 3. Carotenoids are distribution in cytoplasmic vesicles (lipid globules) and transported to and associated with membrane as protective molecules (Havaux, 1998; Erasun and Johnson, 2018) and improved by this review.

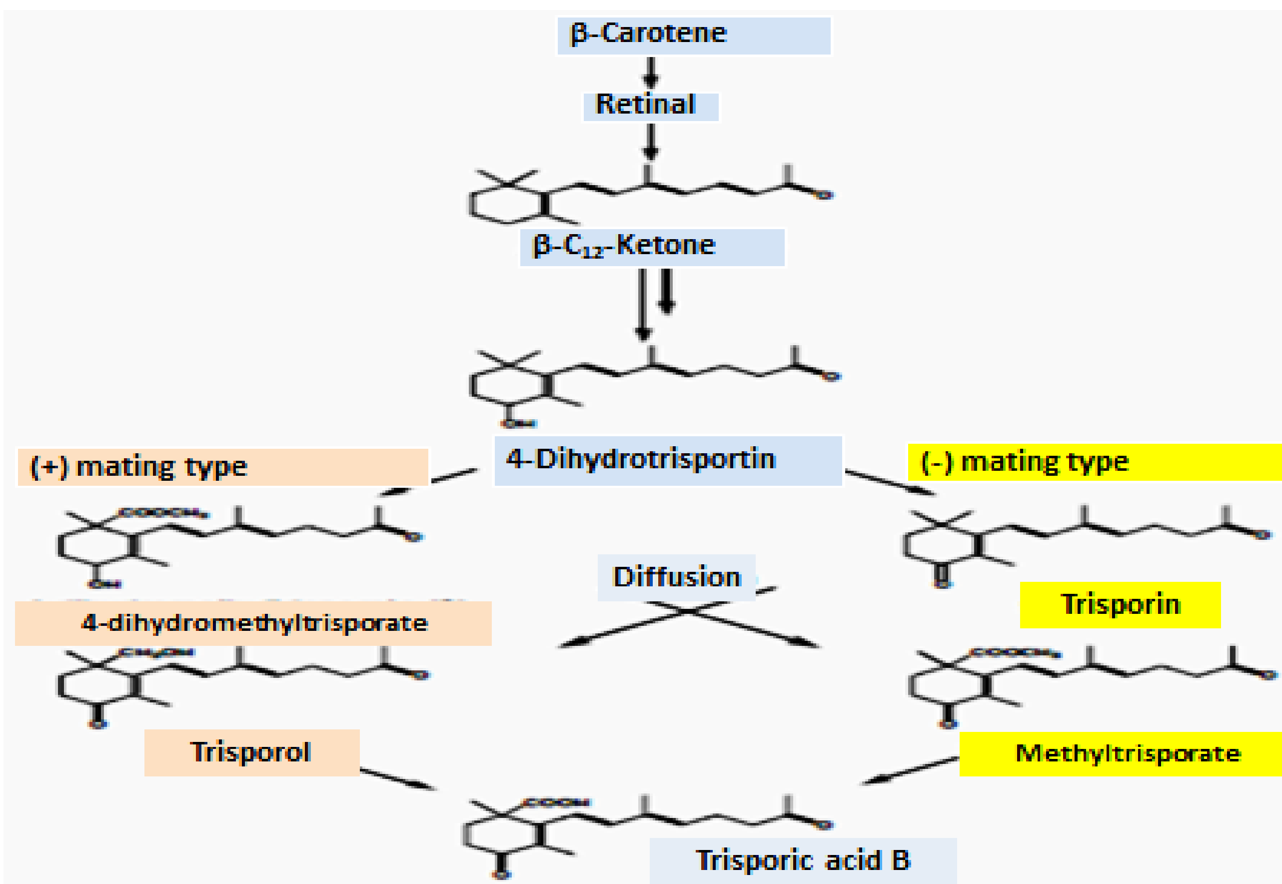


Figure 4. β-carotenes as a precursor of trisporic acid biosynthesis in Zygomycetes.

Table 2. Diversity of carotenoids in different fungal groups (40 genera and 70 species).

I. MYXOMYCOTA (prokaryotes) Myxomycetous fungi (slime molds)		
It produced β-Carotene, γ-Carotene, 3,4-didehydrolycopene & neurosporaxanthin		
II. EUMYCOTA		
II₁. Mastigomycotina		
Phylum and orders	Genus and species	Carotenoids derivatives recorded
Chytridiomycetes	Many genera and species	β-Carotene, γ-Carotene & lycopene
Oomycetes	Un valid	Un valid
II₂. Zygomycotina		
	Blakeslea trispora (Rhizomucor miehei)	β-carotene, δ-carotene & lycopene.
	Phycomyces blakesleeanus	β-carotene and δ-carotene.
Mucorales	*Phycomyces blakesleeanus*	β-carotene, δ-carotene, lycopene & phytoene
	Choanephora cucurbitarum, *Mucor circinelloides, Pilobolus*	β-carotene
	Erwinia uredovora	Lycopene
Zygomycetes	Many genera and species	Canthaxanthin, β-cryptoxanthin, echinone, zeaxanthin
II₃. Ascomycotina		
Hemiascomycetes	Un valid	Un valid
Dothideomycetes	*Cercospora nicotianae*	Lycopene
Plectomycetes	Many genera and species	β-Carotene, γ-Carotene & lycopene
	Paecilomyces	Carotenoids
Eurotiomycetes, Eurotiales, Trichocomaceae	*Penicillium atrovenetum*	Carotenoids
	Penicillium herquei	Carotenoids
	Penicillium species	Tangeraxanthin and 4-ketonostoxanthin
Eurotiomycetes	*Monascus purpureus*	Carotenoids
Eurotiales, Elaphomycetaceae	*Monascus roseus*	Canthaxanthin
Pyrenomycetes	Many genera and species	β-carotene, γ-carotene, 3,4-didehydrolycopene, torulene, aleuriaxanthin, plectaniaxanthin, phillipsiaxanthin
Discomycetes	β-carotene, γ-carotene, neurosporene, torulene, aleuriaxanthin, plectaniaxanthin & phillipsiaxanthin	
	Cordyceps	Carotenoids
Sordariomycetes Hypocerales	*Fusarium sporotrichioides*	β-carotene, δ-carotene & lycopene
	Fusarium moniliform (Gabriella fujikuroi)	Phytoene
Pezizomycotina Sordariomycetes	*Neurospora crassa*	β-carotene, δ-carotene & phytoene

Table 2. Contd.

Pezizomycotina, Pezizales, Helvellaceae, Morchellaceae	*Helvetia crispa, Helvetia esculenta*, *Helvetia gigas*, *Helvetia infula*, *Helvetia lacunosa*, *Helvetia monachella, Helvetia pallescens*, *Helvetia pezizoides*, *Discina ancilis*, *Discina reticulata*, *Disdotis venosa*, *Leptopodia elastica*, *Paxina acetabulum, Ehizina inflate*, *Morchella conica*, *Morchella esculenta, Verpa digitaliformis*	neurosporene, lycopene, ß-carotene, γ-carotene, α-carotene, flavoxanthin, mutatochrome, ß-zeacarotene, aleuriaxanthin, aleuriaxanthin ester, Astaxanthin, canthaxanthin, ß-cryptoxanthin, lycoxanthin, neurosporaxanthin, rubixanthin, plectaniaxanthin, torularhodin, 3,4-dehydro lycopene, hydroxy-α-carotene, dihydroxy-C-carotene, 1,2,1',2'-tetrahydro-1, l'-dihydroxy lycopene
Saccharomycetes	*Yarrowia, Zygosaccharomyces rouxii* (yeast)	Carotenoids
Loculoascomycetes	*Cyberlindnera jadinii* (*Candida utilis*) GE, *Pichia pastoris by GE*, *Saccharomyces cerevisiae* by GE	Non carotenogensis yeast converted by genetic engineering to carotenoids producers on large scales
II_4.Basidiomycotina		
Filobasidiales	*Dioszegia hungarica*	Carotenoids
Tremellales	*Cryptococcus aerius, laurentii, magnus & victoria*	Carotenoids
Cystofilobasidiales	*Cystofilobasidium capitatum*	β-carotene, γ-carotene, torulene & torularhodine
Leucosporidiales	*Leucosporidiella muscorum*	
Phylum and orders	Genus and species	Carotenoids derivatives recorded
Hymenomycetes		β-carotene, γ-carotene, astaxanthin, canthaxanthin, cryptoxanthin & diadinoxanthin
Gasteromycetes		β-carotene, γ-carotene
Teliomycetes		β-carotene, γ-carotene, torulene, phytoene, cryptoxanthin & β-zeacarotene
Basidiomycetous, Microbotryomycetes, *Sporidiobolales*	*Rhodotorula aurantiaca, Rhodotorula acheniorum, Rhodotorula graminis, Rhodotorula glutinis, Rhodotorula minuta & Rhodotorula mucilaginosa* (Red yeasts)	Carotenoids β-carotene, γ-carotene, torulene, torularhodin, antheraxanthin & echinenone
Sporidiobolales	*Rhodosporidium babjevae, Rhodosporidium Minuta, Rhodosporidium diobovatum & Rhodosporidium sphaerocarpum*	β-carotene, torulene & torularhodine
Sporidiobolales	*Sporidiobolus salmonicolor*	
	Sporobolomyces pararoseus, Sporobolomyces roseus, Sporobolomyces salmonicolor & *Sporobolomyces patagonicus* yeast	β-carotene, torulene & torularhodine
	Xanthophyllomyces dendrorhous (*Paracoccus* species)	
Agaricomycotina Termellomycetes	*Phaffia rhodozyma* (*Rhodomyces dendrorhous) & Phaffia paxilli* east	Astaxanthin
Agaricomycetes Edible mushrooms	*Russula virescens*	β-carotene & lycopene

Table 2. Contd.

	Cantharellus cibarius, Cantharellus minor, Cantharellus friesii & *Cantharellus cinnabarinus*	β-carotene Canthaxanthin
II5. Deuteromycotina	*Choanephora cucurbitarum*	β-carotene, γ-carotene & torularhodine
	Liakopoulou-Kyriakides	β-carotene, γ-carotene & torularhodine

Table 3. Metabolic engendering produced insoluble and orange-colored natural pigment.

Carotenoids derivative	Tested fungus	Ideal conditions for maximum pigment production	References
-	Cold adapted *Penicillium* species (GBPI_P155)	Potato dextrose (PD) broth, 2% maltose, 15°C & extracted by chloroform. Tested by UV/vis (λmax at 495 nm and a shoulder peak at 530 nm) and Fourier Transform Infrared (FT-IR) spectroscopy.	Pandey et al. (2018)
Carotene	Pp-EBILWZ) *Pichia pastoris* yeast	YPD (yeast extract 1%, peptone 2%, and glucose 2%) + 200 µg/mL Zeocin. After 72 h & 200 rpm, at 30°C& extracted by distilled water	Araya-Garay et al. (2012)
Carotenoids	*Rhodotorula acheniorum, Rhodotorula glutinis* & *Rhodotorula mucilaginosa*	radish brine, mung bean waste flour, sweet potato extract, whey, chicken feathers, crude glycerol, whey	Mata-Gómez et al. (2014), Erasun and Johnson (2018)
UV-light Stimulator 250% Carotenoids			
Astaxanthin & Cantaxanthin	*Rhodotorula glutinis*	O_2 flow 30°C	
Stimulator carotenoids	*Rhodotorula glutinis*	Metal ions and salts (Ba, Fe, Mg, Ca, Zn and Co)	
Stimulator β – and γ- carotene	*Rhodotorula glutinis*	Al_3^+ and Zn_2^+	
torulene & torularhodin	*Rhodotorula glutinis*	Zn^{2+} and Mn^{2+} Inhebited the	Yen and Zhang (2011)
Astaxanthin	*Phaffia rhodozyma*	ethanol (10 g L-1) and acetic acid (5 g L^{-1})	
Carotenoids	*Xanthophyllomyces dendrorhous*	Addition of 0.2% (v/v) ethanol to cultures	
Carotenoids	*Rhodotorula glutinis*	C & N_2 source 25-43%	
Torulene	*Rhodotorula glutinis*	C & N_2 source 28-30%	

Murugesan, 2017; Kot et al., 2018; Erasun and Johnson, 2018; Czeczuga, 1979) (Table 2).

Development of fungal carotenoids productivity by metabolic engineering

Many authors reviewed the maximization and development of the yeast carotenoids productivity by metabolic engineering through environmental and nutritional factors controlled (Table 3), screening and selecting the hyper-producer strains (Figure 5), and optimization and maximization of their carotenoids productivity by metabolic engineering (controlling in the nutritional and environmental factors) (Table 3 and Figure 5).

Development the fungal carotenoids productivity by extraction techniques

Mata-Gómez et al. (2014) studied the effect of different extraction methods on the amount of carotenoids produced from yeast cells and HCl and acetone methods were the most effective distribution technique (Table 4).

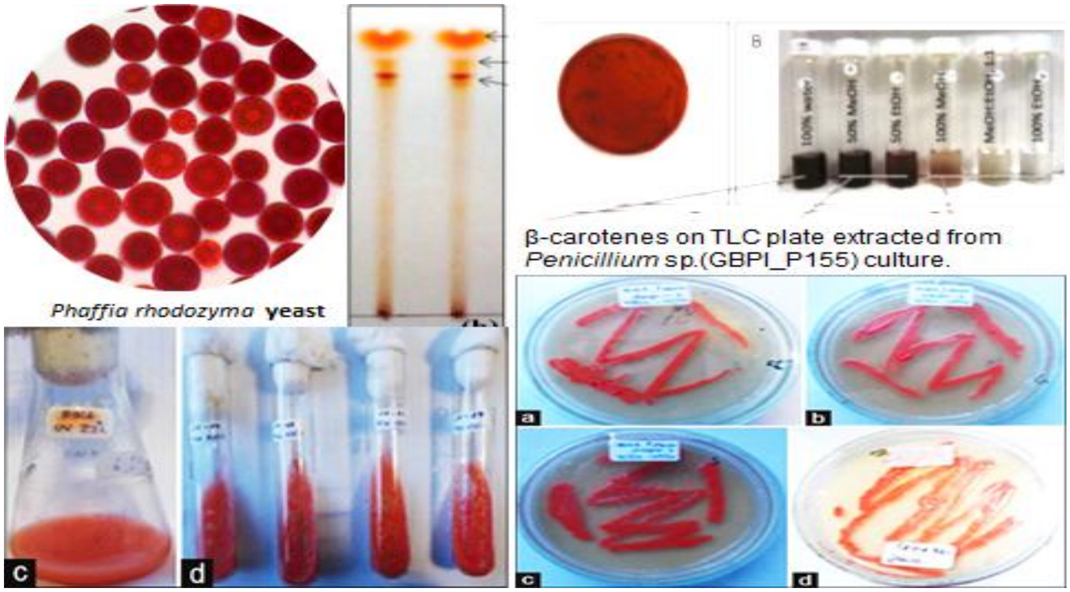


Figure 5. β-carotenoids produced from many yeast and *Penicillium* by metabolic engineering.

Table 4. Carotenoids amount are affected by different extraction techniques (Mata-Gómez et al., 2014).

Disruption technique	Yeast	Carotenoids yield (mg/biomass)
Freezing and maceration with diatomaceous earth	*Phaffia rhodozyma*	0.093
Freezing and DMSO	*Phaffia rhodozyma*	0.156
Enzymatic lysis and ultrasonic waves	*Phaffia rhodozyma*	0.163
HCl and acetone	*Rhodobacter sphaeroides*	4.790
DMSO, acetone and petroleum ether	*Rhodotorula graminis*	0.803
Freezing in liquid N2 and maceration	*Sporoidiobolus salmonicolor*	0.590 mg/L of medium
Freeze-dried	*Rhodotorula glutinis*	0.266
DMSO, acetone and petroleum ether	*Rhodotorula glutinis*	92 mg/L of medium
Bead grinder	*Rhodotorula glutinis*	125 mg/L of medium

Development of the yeast carotenoids productivity by genetic engineering

The ideal strategy to increase carotenoids production and reduce the costs of production in yeast is by metabolic and genetic engineering. Application of genetic engineering in yeasts by:

(1) Selection of the hyper-producer strains of carotenoids producers.
(2) Improvement of their productivity by metabolic engineering.
(3) Obtaining the carotenogenic genes from the yeast hyper-producer strains such as *Erwinia uredovora*, *Agrobacterium aurantiacum* and *Xanthophyllomyces dendrorhus*.
(4) Insertion of carotenogenic genes (β-carotene, lycopene and astaxanthin gene) in non-carotenogenic yeast such as *S. cerevisiae*, *P. pastoris* and *C. utilis*.

These yeasts are very useful in food industries, safe yeast with many advantages as easy genetic manipulation with established host-vector systems (Verwaal et al., 2007; Voigt et al., 2016; Erasun and Johnson, 2018).

CONCLUSION

The fungal carotenoids have many advantages to improve the food quality and industrial development, which represent the ideal method for dissolving the production coloring problems around the world and giving suitable supplementation amounts. More recently genetic engineering of the non carotenogenesis yeast *S. cerevisiae, Candida utile* and *P. pastoris* is promising to the world by more development of carotenoids production.

Table 5. Classification of the fungal carotenoids into two large groups with chemical structures, molecular formula, color of 34 carotenoids derivatives synthesized by fungi.

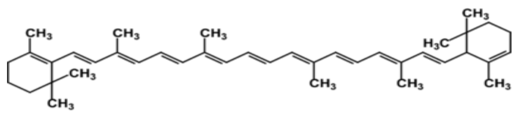
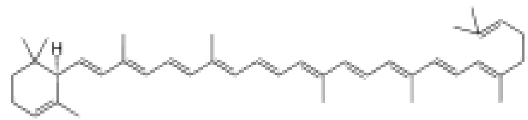
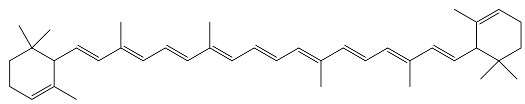
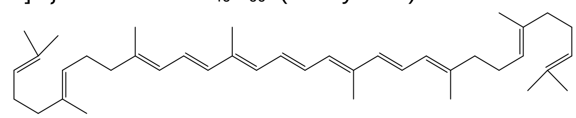
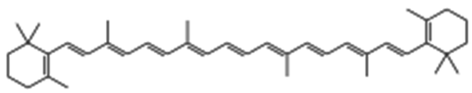
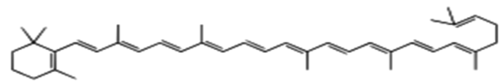
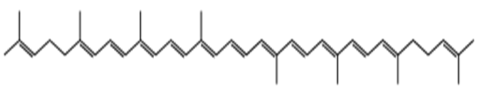
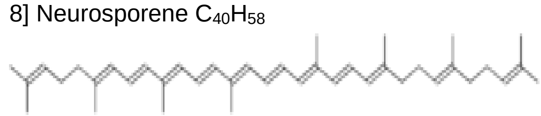
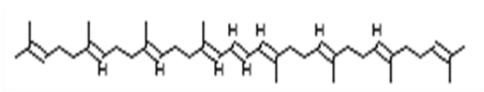
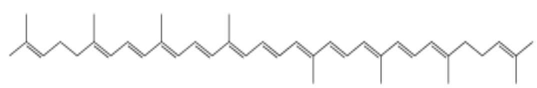
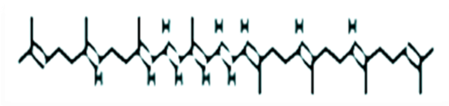
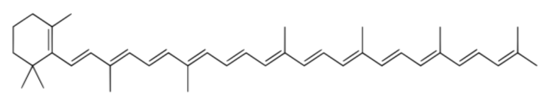
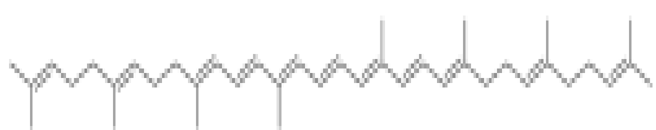
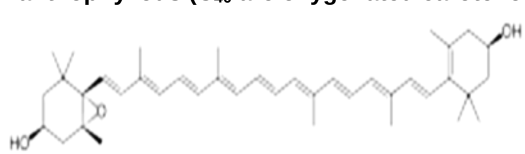
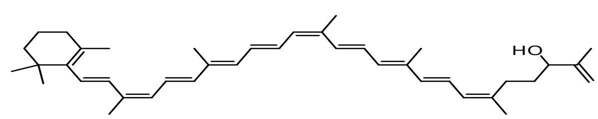
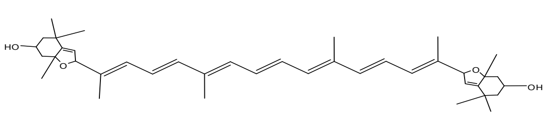
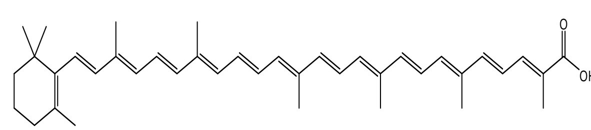
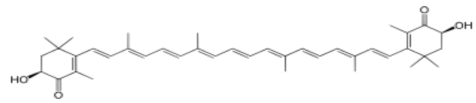
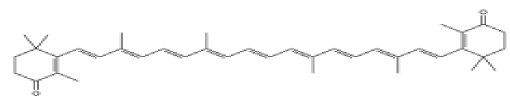
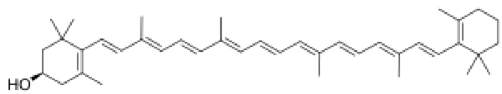
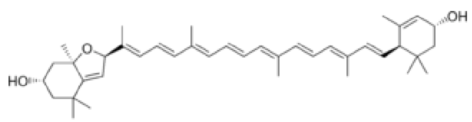
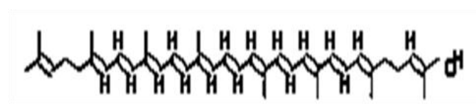
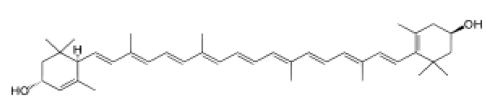
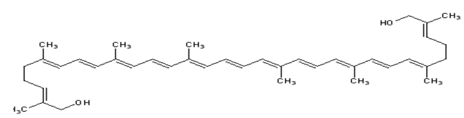
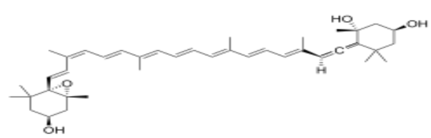
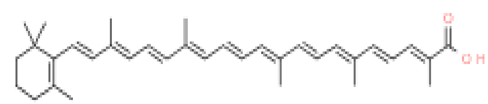
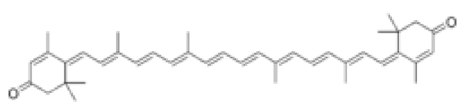
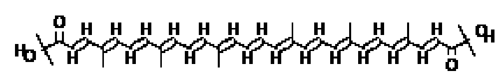
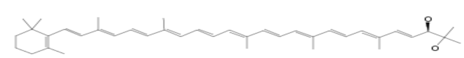
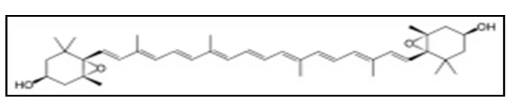
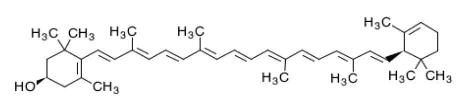
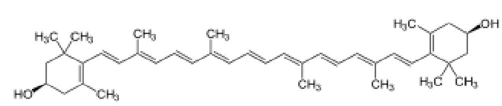
Carotenoids name, molecular formula (Color)	**Chemical structures (Pub Chem)**
Nonoxygenated fourteen carotenes have C_{40}	
1] α-Carotene $C_{40}H_{56}$ (yellow) 	2] δ –Carotene $C_{40}H_{56}$ (Pale yellow) 
3] ε-Carotene $C_{40}H_{58}$ (Pale yellow) 	4] ζ- –Carotene $C_{40}H_{60}$ (Pale yellow) 
5] β -Carotene $C_{40}H_{56}$ (Yellow to orange) 	6] γ- -Carotene $C_{40}H_{56}$ (Yellow to orange) 
7] Lycopene $C_{40}H_{56}$ (Red) 	8] Neurosporene $C_{40}H_{58}$ 
9] Phytoene $C_{40}H_{64}$ (Colorless) 	10] Lycoperesne $C_{40}H_{56}$ 
11] Phytofluene $C_{40}H_{62}$ 	12] Torulene $C_{40}H_{54}$ (Pink) 
13] β-Zeacarotene $C_{40}H_{56}$ 	
Xanthophyllous (C_{40} are oxygenated carotenoids) metabolites	
 1] Antheraxanthin $C_{40}H_{56}O_3$ (Bright yellow)	 2] Aleuriaxanthin $C_{40}H_{56}O$
 3] Aureoxanthin $C_{40}H_{56}O_4$	 4] Torularhodin $C_{40}H_{52}O_2$ (Orange)

Table 5. Contd.

 5] Astaxanthin $H_{52}O_4$ (Red-pink)	 6] Canthaxanthin $C_{40}H_{52}O_2$ Orange –Pink
 7] Cryptoxanthin $C_{40}H_{56}O$ (Orange)	 8] Echinenone $C_{40}H_{58}O_3$
 9] Flavoxanthin $C_{40}H_{58}O_3$ (golden-yellow)	 10] Lycoxanthin $C_{40}H_{56}O$
 11] Lutein $C_{40}H_{56}O_2$ (yellow)	 12] Lycophyll $C_{40}H_{56}O_2$ (Red)
 13] Neoxanthin $C_{40}H_{56}O_4$ (Yellow)	 14] Neurosporaxanthin $C_{35}H_{46}O_2$
 15] Rhodoxanthin $C_{40}H_{50}O_2$ (Purple)	 16] Phillipsiaxanthin $C_{40}H_{52}O_4$
 17] Rubixanthin $C_{40}H_{56}O$ (Natural Yellow 57)	 18] Plectaniaxanthin $C_{40}H_{56}O_2$
 19] Violaxanthin $C_{40}H_{56}O_4$ orange to purple	 20] Zeinoxanthin $C_{40}H_{56}O$ (red-orange)
 21] Zeaxanthin $C_{40}H_{56}O_2$ (yellow)	

CONFLICT OF INTERESTS

The author has not declared any conflict of interests.

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