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Fucoxanthin and lipid metabolism: a minireview

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Abstract

Aims

Accumulating data suggest that food supplementation with seaweeds which traditionally are an important part of food culture in South-East Asian countries might lead to essential health benefits. In this short review, we summarize findings from experimental studies on the effects of fucoxanthin (a carotenoid derived from brown seaweeds) on lipid metabolism, adiposity, and related conditions and discuss the possible underlying mechanisms.

Data synthesis

Supplementation of fucoxanthin or its derivatives consistently attenuated body and visceral fat weight gain, lipid accumulation in the liver, decreases insulin resistance, and improves the plasma lipid profile in rodents fed a high-fat diet. It should however be noted that in diabetic/obese KK-A¹ mice with genetically compromised insulin signaling, fucoxanthin might increase the plasma levels of cholesterol and low-density lipoproteins. The anti-obesity effects of fucoxanthin are apparently mediated by the hormones leptin and adiponectin through their common target AMPK-activated protein kinase, resulting in downregulation of lipogenic enzymes and upregulation of lipolytic enzymes. Fucoxanthin also suppresses adipocyte differentiation and induces the expression of uncoupling proteins in visceral adipose tissue.

Conclusions

The results of experimental studies suggest that consumption of fucoxanthin and its derivatives as nutritional supplements is a promising option for prevention and treatment of obesity and a wide variety of related pathologies, including metabolic syndrome, type 2 diabetes, and heart disease. Yet, clinical trials are warranted to assess a therapeutic value of fucoxanthin.
Introduction

Food resources have always been limiting factors in the Darwinian struggle for existence and have shaped mechanisms of energy storage during evolution. This impact in terms of energy storage has however become a serious disadvantage for populations in developed countries as excessive fat accumulation that results from excessive energy storage is a well-known risk factor for many syndromes and diseases [1]. In the last years, overweight is an emerging challenge for developing countries as well [2]. The growing number of obese people is approaching an epidemiological disaster and calls for the urgent development of means to normalize lipid metabolism, including successes in nutrigenomics, personalized nutrition programs, and the application of specific “fat burners” [3-5].

The modification of adipose tissue is a delicate issue because adipocytes are important participants in many functional systems, including thermoregulatory, endocrine and immunological responses. Adipose tissue is currently recognized as a major endocrine organ in the production and secretion of leptin, adiponectin, resistin, estrogen, secretin, steroids, cytokine TNFα, and other bioactive compounds [6,7]. Furthermore, specific adipocytes in adipose tissue play an important role in the determination of metabolic rate. While the white adipocytes mainly serve as a storage depot for high-energy compounds (e.g. triglycerides), the brown adipocytes actively metabolize lipids and glucose to produce heat. When activated, the energy expenditure of brown adipose tissue (BAT) could exceed the energy demand of other tissues by several hundred times. Consequently, excessive white adipose tissue (WAT) has a negative impact on health, whereas the activation of brown adipocytes can increase metabolic rate and provide beneficial effects on adiposity, insulin resistance and hyperlipidemia [8-10].

WAT can potentially undergo “browning” due to newly-differentiated beige adipocytes. The beige adipocytes are induced in WAT in response to various physiological or hormonal activators (e.g., cold or melatonin) [11,12]. Unlike the developmentally programmed brown cells, the induced beige cells are derived from precursors closer to the white adipocyte cell lineage. There is a growing interest in beige cells because their induction could significantly redistribute organismal energy expenditure and lipid metabolism. Remarkably, brown and beige cells are widely dispersed and show unexpectedly high activity in humans, positively correlating with human leanness [13,14].

Recent years have been marked by the emergence of another vibrant research area related to lipid metabolism – the study of the marine carotenoid fucoxanthin (FX) and its derivatives. These substances are beneficial for the treatment of a surprisingly wide variety of dysfunctions and diseases, including metabolic syndrome, obesity, heart disease, diabetes, cancer,
hypertension, as well as ROS- and inflammation-associated disorders [15-21]. Here, we briefly discuss possible causes of FX bioactivities, focusing on its specific effects on lipid metabolism.

**FX sources and toxicity**

Although carotenoids can be synthesized chemically, their extraction from macroalgae and microalgae is a more accessible, safe, and economic source of FX. The list of edible seaweeds that contain FX is impressive and includes Undaria pinnatifida, Hijikia Fusiformis, Sargassum fulvellum, Chaetoseros sp., Eisenia bicyclis, Kjellmaniella crassifolia, Alaria crassifolia, Sargassum horneri, Cystoseira hakodatensis, Laminaria japonica, Undaria pinnatifida, and Sargassum fusiforme [16,22]. These and other algae may significantly differ in their content and yield of extracted FX. For instance, the diatom Phaeodactylum tricornutum contains at least ten times more FX than seaweeds [26]. FX-rich seaweeds have traditionally been used in Southeast Asia (mostly Japan, Korea and China) as nutrients for pregnant women and nursing mothers, as well as remedies for blood purification, skin rejuvenation, improving reproduction, and digestion [20,24,25]. As they are of natural origin, FX and most other marine carotenoids exhibit low-toxicity. For example, a study of FX-enriched oil extracted from the microalgae Chaetoseros sp. showed no signs of genotoxicity in the bacterial reverse mutation test and micronucleus test in mice [26]. In addition, in a rat study, the 50% lethal single dose of FX was more than 2 g/kg of body weight and no elevated mortality or abnormalities were observed in a 13-week oral administration of FX in a dose of 200 mg/kg [27].

**FX stimulates lipolysis and inhibits lipogenesis**

Lipolysis and lipogenesis are two opposing processes that determine the level of stored fat and the rate of lipid metabolism. Adiponectin and leptin are two protein hormones exclusively secreted from adipose tissue and are the main regulators of body weight gain, primarily stimulating fatty acid oxidation in peripheral tissues (via activation of AMP-activated protein kinase) and acting antagonistically on the central control of food intake by increasing and decreasing food intake, respectively [28]. The main effects of FX on lipid metabolism and adiposity are presented in Summary Table. In obese mice fed a high-fat diet (20% fat), the application of FX (0.05 or 0.2% wt/wt for 6 weeks) decreased adipocyte size, body weight gain and visceral fat-pads without altering the food intake [29]. The latter could be attributed to the opposite FX-induced alterations in adiponectin and leptin: FX-treated mice had increased
Adiponectin levels and decreased leptin levels in plasma. The mRNA expression and activity of lipogenic enzymes were significantly downregulated in a dose-dependent manner in epididymal adipose tissue, with simultaneous upregulation of fatty acid β-oxidation [29]. In another study on mice fed a high fat diet, application of the whole seaweed Petalonia binghamiae, or FX extracted from it, also decreased body and adipose tissue weight gain as well as serum triglyceride [30]. Extracts from Petalonia binghamiae reduced the accumulation of lipid droplets in the liver and suppress the serum levels of alanine and aspartate transaminases, indicating improvements in liver function. FX increases the phosphorylation of AMP-activated protein kinase and its downstream target acetyl-CoA carboxylase in mature adipocytes and in epididymal adipose tissue, thereby reducing lipogenesis and simultaneously promoting the β-oxidation of fatty acids [30]. Similarly, supplementation of a high-fat diet of obese mice with 0.2% FX, or an equivalent amount of ethanol extract from the seaweed Undaria pinnatifida, over nine weeks decreased visceral fat deposits, adipocyte size, and hepatic lipid droplet accumulation as a result of activated fatty acid β-oxidation [31]. This was accompanied by beneficial effects on glucose homeostasis, including a decrease in fasting blood glucose, plasma insulin content, and insulin resistance. Interestingly, the blood glucose level negatively correlated to hepatic glucokinase activity and positively correlated to the activities of the hepatic gluconeogenic enzymes glucose-6-phosphatase and phosphoenolpyruvate carboxykinase. The glycogen content and ratio of hepatic glucokinase/glucose-6-phosphatase were also significantly elevated in the FX-treated animals [31].

In rats fed a high-fat diet (20% fat), FX supplements (0.2%) increased the levels of plasma high-density lipoproteins but decreased the levels of hepatic total lipids, total cholesterol, and triglycerides [32]. FX application also decreased the mRNA expression of key initial lipogenic factors, such as hepatic acetyl-CoA carboxylase and acyl-CoA cholesterol acyltransferase, as well as the activities of fatty acid synthase and glucose-6-phosphate dehydrogenase. Remarkably, the expression of these enzymes in rats fed a high-fat diet supplemented with FX did not differ significantly from those fed a normal (7% fat) diet [32].

In obese mice, FX supplementation increased the content of non-digested fecal lipids and decreased hepatic lipids which could be attributed to the reduced activity of hepatic lipogenic enzymes, such as glucose-6-phosphate dehydrogenase, malic enzyme, fatty acid synthase and phosphatidate phosphohydrolase, along with an enhanced fatty acid β-oxidation [33]. In blood plasma, FX increased high-density lipoproteins (HDL) and cholesterol-suppressing activities of two key cholesterol-regulating enzymes, 3-hydroxy-3-methylglutaryl coenzyme A reductase and acylcoenzyme A: cholesterol acyltransferase. These changes were accompanied by a
decrease in blood glucose and HbA1c levels, as well as decreased plasma resistin and insulin concentrations [33]. Along with anti-obese effects (decreasing body and WAT weight gain), FX completely normalized hyperglycemia, hyperinsulinemia, and hyperleptinemia induced by a high-fat diet in mice [34]. Normalization of glucose levels could in part be attributed to FX-promoted expression of glucose transporter mRNA in skeletal muscle (which facilitates the cellular uptake of glucose from the blood) and an increased insulin sensitivity. Also, the decrease in leptin production (as a result of a lower WAT weight in FX-treated mice) was apparently accompanied by elevation in sensitivity to this hormone. Both effects of FX could be mediated by stearoyl-coenzyme A desaturase-1, a rate-limiting enzyme that catalyzes the biosynthesis of monounsaturated fatty acids from saturated fatty acids. Its downregulation prevents obesity and improves sensitivity to insulin and leptin. Indeed, in diabetic/obese KK-Ay mice, FX (0.2% for 4 weeks) significantly decreased stearoyl-coenzyme A desaturase-1 mRNA and protein expression, body weight gain and serum leptin levels, as well as the hepatic oleic/stearic acid ratio [35]. The role of leptin in mediating the anti-obese effects of FX gained further support from the observation that they were completely abrogated in leptin-deficient ob/ob mice [35]. The FX-induced increase in expression of β3-adrenergic receptor in WAT could be an addition factor for enhancing lipogenesis in obese mice [34].

It is important to stress that FX exerts its anti-obese and other specific effects on obese mice but not on lean mice. As in a high-fat fed mice [29,30,31,33,34,36], FX attenuated body and WAT weight gain and normalized blood glucose levels in diabetic/obese KK-Ay mice, without any significant effect on these variables in control (lean) C57BL/6J mice [37]. Also, expression of monocyte chemoattractant protein-1 and tumor necrosis factor-α (TNFα) mRNA was suppressed in WAT of KK-Ay mice but not in WAT of lean C57BL/6J mice [37]. This suggests that FX does not modify constitutively active mechanisms but suppresses excessively elevated or high fat-induced pathways of lipid metabolism by stimulating lipolysis and suppressing lipogenesis.

**Combination of FX with oils**

Because FX is a hydrophobic substance, its dissolution, absorption, and transport through inter- and intracellular barriers could be enhanced by its combination with other oils, eventually increasing the ability of FX to improve lipid metabolism and plasma lipid profile, and reduce body and liver fat content. Several lines of evidence are in support of this notion. For instance, the anti-obese effects of FX in mice were increased through its combination with medium-chain triacylglycerols, so that the visceral fat weight gain was markedly lower and metabolic
thermogenesis in WAT was markedly higher in diabetic/obese KK-A\textsuperscript{y} mice fed a mixture of FX (0.1\%) and medium-chain triacylglycerols (0.9\%) than in mice fed with FX (0.1\%) only [38]. The application of FX with conjugated linoleic acid to the high-fat (15\% fat) diet of rats resulted in reduced serum levels of triacylglycerol, glucose, and leptin, and these effects were more pronounced than the effects of FX alone [39]. The application of FX with fish oil also improved the FX effects associated with obesity. The combination of 0.1\% FX with fish oil (6.9\%) attenuated WAT weight gain and decreased blood glucose levels in diabetic/obese KK-A\textsuperscript{y} mice to a similar extent as 0.2\% FX alone, suggesting that the mixture of FX and fish oil was almost twice as effective as a pure FX [40].

FX and its deacetylated derivative, fucoxanthinol, almost doubled the content of hepatic docosahexaenoic acid, a highly important n-3 functional polyunsaturated fatty acid in biological systems [15,41]. Application of FX extracted from brown seaweed Undaria pinnatifida with n-3 polyunsaturated fatty acid-rich scallop phospholipids to the diet of KK-A\textsuperscript{y} mice during 4 weeks reduced body and WAT weight gain more efficiently than these bioactive lipids given separately [42].

Xanthigen is a promising combination of FX and pomegranate seed oil containing up to 70\% of punicic acid (an omega-5 long chain polyunsaturated fatty acid). The high efficiency of xanthigen in improving the lipid metabolism was shown in both experimental and clinical studies. In the in vitro study on 3T3-L1 preadipocytes, xanthigen suppressed the adipocyte differentiation and accumulation of lipid droplets more efficiently than its components, FX and pomegranate seed oil [43]. Further analysis revealed that among key events which could mediate these effects are downregulation of peroxisome proliferator-activated receptor \( \gamma \) (PPAR\( \gamma \)), CCAAT/enhancer binding proteins (C/EBP) \( \beta \) and \( \delta \), and fatty acid synthase, with concomitant upregulation of AMP-activated protein kinase signaling pathways [43].

Clinical trial of xanthigen demonstrated its remarkable anti-obesity activity in humans. In a 16-week study of the effects of xanthigen in 151 obese, non-diabetic, premenopausal female volunteers [44], it was found that xanthigen 600/2.4 (300 mg pomegranate seed oil plus 300 mg brown seaweed extract containing 2.4 mg FX) resulted in a significant decrease in body weight, liver fat content, and serum triglycerides, accompanied by improvement of liver function tests. Xanthigen 400/1.6 mg (200 mg pomegranate seed oil plus 200 mg brown seaweed extract containing 1.6 mg FX) and FX (> 2.4 mg) also increased resting energy expenditure.

The overall results indicate that combination of FX with oils and xanthigen in particular potentiate the anti-obese effects of FX, and thus, may be promising food supplements for the treatment of obesity.
FX and UCP

Uncoupling proteins (UCPs) are a family of mitochondrial proteins that dissipate the proton gradient of the inner mitochondrial membrane and are primarily responsible for non-shivering thermogenesis [45]. Accordingly, USPs are believed to be a promising therapeutic target in treating obesity and related pathologies [45, 46]. Feeding FX to mice upregulated mitochondrial UCP1 mRNA and protein, leading to excessive heat production and the oxidation of fatty acids of adipocytes in WAT [36,47]. In another study, FX increased the mRNA expression of UCP-2 in visceral WAT, concomitant with UCP-1 and UCP-3 expression in BAT [29]. As could be expected (see previous section), obese mice fed a mixture of FX and medium-chain triacylglycerols [38] or FX with fish oil [40] had a markedly higher UCP1 expression in WAT compared to mice fed FX alone, apparently due to the increased absorption rate of oil-solubilized FX.

FX suppresses adipocyte differentiation

Another important pathway for preventing abnormalities in lipid metabolism is associated with the suppression of adipocyte differentiation. FX and especially its metabolites (e.g., fucoxanthinol and amarouciaxanthin) inhibited murine preadipocyte differentiation into mature adipocytes by suppressing intracellular lipid accumulation and glycerol-3-phosphate dehydrogenase activity, which are indicative of induced adipocyte differentiation [48]. In view of the key role of PPARγ in stimulating the genes responsible for lipid uptake and adipogenesis [49], the inhibition of PPARγ mRNA expression could be a key event [48].

Preadipocyte differentiation into adipocytes is divided into early (days 0-2), intermediate (days 2-4), and late stages (days 4-7). It appears that the FX effects on adipogenesis depend on adipocyte differentiation stage: FX paradoxically promoted adipocyte differentiation during the first two days and inhibited differentiation at later stages [50]. As shown on 3T3-L1 cells, at the initial stage, FX upregulated, in a dose-dependent manner, the expression of adipogenic factors PPARγ, C/EBPa, sterol regulatory element-binding proteins 1c and aP2, and adiponectin mRNA. These alterations were accompanied by triglyceride accumulation. At intermediate and late stages of preadipocyte differentiation, however, FX inhibited the expression of the above-mentioned genes and decreased glucose uptake by reducing the phosphorylation of insulin receptor substrate 1 [50,51].
Amarouciaxanthin is the dominant FX metabolite in WAT. A comparative study on the effects of FX, fucoxanthinol, isofucoxanthinol, and amarouciaxanthins A and B on the differentiation of 3T3-L1 cells showed that all of these compounds decreased the activity of glycerol-3-phosphate dehydrogenase and suppressed adipocyte differentiation [52]. The suppressive effect of amarouciaxanthin A was however stronger than the other compounds tested. Further analysis revealed that the mRNA and protein expression of key adipogenic transcription factors, PPARγ and C/EBPα, as well as transcription of the late markers of adipocyte differentiation (adipocyte fatty acid-binding protein, lipoprotein lipase, glucose-transporter 4) were downregulated by amarouciaxanthin A and to a lesser degree by fucoxanthinol [52].

**Concluding remarks**

Increasing data suggests that FX and its derivatives could become important ingredients in human and animal health supplements, foods, and cosmetics. They are low-toxicity and natural products that effectively attenuate body and WAT weight gain as well as hyperglycemia in genetically modified diabetic/obese KK-A^y^ mice or normal animals under high-fat diets. However, many important issues remain to be elucidated. Although FX is known as a “fat burner”, it might increase blood cholesterol levels – an important issue in diseases such as atherosclerosis. In diabetic/obese KK-A^y^ mice fed FX for 4 weeks, the serum content of cholesterol and low-density lipoproteins significantly increased, whereas hepatic cholesterol levels and hepatic proteins involved in cholesterol uptake decreased [53]. This suggests that in case of genetically compromised insulin signaling, FX could increase blood cholesterol levels by inducing cholesterol synthesis and reducing its uptake in the liver [53]. It should however be emphasized that this undesirable elevation in plasma total cholesterol and especially low-density lipoproteins (LDL) was shown only in a single study on a genetically modified mouse model [53] and was not observed in numerous experimental studies of FX-treated normal animals under high-fat diets (see Summary Table). Moreover, in case of alimentary obesity, FX either did not affect or even decreased the levels of total cholesterol in plasma, accompanied by a favorable redistribution of plasma lipid fractions towards an increase in the HGL/LDL ratio and a decrease in triglycerides. In the single clinical observation carried out thus far on adiposity and dyslipidemia in obese, non-diabetic women, a beneficial effect of xanthigen (a mixture of FX and pomegranate seed oil) was also shown [44]. Yet, clinical trials are warranted to assess a therapeutic value of fucoxanthin.
Another important issue involves the potential of FX to induce the differentiation of beige adipocytes. This effect could cause FX to have sustained anti-obesity effects even after the cessation of drug intake. However, it is worth mentioning that FX and its derivatives apparently have low prophylactic value because they act through a set of genes induced by pathological conditions or high fat diets, but do not show obvious effects on the lipid metabolism of lean mice kept on normal diets [37]. Moreover, the ever growing list of food supplements claiming to improve fat metabolism is impressively long and includes caffeine, green tea, conjugated linoleic acid, soy isoflavone, carnitine, kelp, catechins, capsaicin, glabridin, forskolin, and many others [4,54]. Whether FX will find its niche in this competitive field remains to be elucidated.

**Potential conflict of interest**

None.

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**Summary Table.** Effects of fucoxanthin supplementation on adiposity and lipid metabolism in rodent models of genetically- or diet-induced obesity.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Effect of FX</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body weight gain</td>
<td>Attenuation</td>
<td>[29, 30, 33-40, 42, 47, 51, 53]</td>
</tr>
<tr>
<td>Food intake</td>
<td>NS</td>
<td>[29-31, 33, 34, 37-40, 47, 51, 53]</td>
</tr>
<tr>
<td>Visceral WAT mass</td>
<td>Decrease</td>
<td>[29-31, 34-40, 42, 47, 51, 53]</td>
</tr>
<tr>
<td>Non-visceral WAT mass</td>
<td>NS</td>
<td>[29]</td>
</tr>
<tr>
<td></td>
<td>Decrease</td>
<td>[36]</td>
</tr>
<tr>
<td>BAT mass</td>
<td>NS</td>
<td>[29, 39]</td>
</tr>
<tr>
<td></td>
<td>Increase</td>
<td>[34, 37, 47]</td>
</tr>
<tr>
<td>Hepatic fat content</td>
<td>Decrease</td>
<td>[29-33, 36, 39; 51, 53]</td>
</tr>
<tr>
<td>Fecal fat excretion</td>
<td>Increase</td>
<td>[32, 33, 36]</td>
</tr>
<tr>
<td>Plasma lipid profile</td>
<td>NS</td>
<td>[34]</td>
</tr>
<tr>
<td>HDL-cholesterol</td>
<td>Increase</td>
<td>[32, 33, 36, 51, 53]</td>
</tr>
<tr>
<td></td>
<td>Decrease</td>
<td>[39]</td>
</tr>
<tr>
<td>LDL-cholesterol</td>
<td>Increase(^b)</td>
<td>[53]</td>
</tr>
<tr>
<td></td>
<td>Decrease</td>
<td>[33, 34, 39]</td>
</tr>
<tr>
<td>Total cholesterol</td>
<td>NS</td>
<td>[32, 33, 34]</td>
</tr>
<tr>
<td></td>
<td>Increase(^b)</td>
<td>[53]</td>
</tr>
<tr>
<td></td>
<td>Decrease</td>
<td>[36, 39]</td>
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<tr>
<td>Triglycerides</td>
<td>NS</td>
<td>[32, 34]</td>
</tr>
<tr>
<td></td>
<td>Decrease</td>
<td>[33, 36, 39, 53]</td>
</tr>
<tr>
<td>Free fatty acids</td>
<td>NS</td>
<td>[36]</td>
</tr>
<tr>
<td>Hormones</td>
<td>Increase in plasma, expression in WAT, and in sensitivity</td>
<td>[29, 39, 51]</td>
</tr>
<tr>
<td>Adiponectin</td>
<td>Increase in plasma, expression in WAT, and in sensitivity</td>
<td>[29, 31, 34, 35, 39, 40]</td>
</tr>
<tr>
<td>Leptin</td>
<td>Decrease in plasma, along with increase in sensitivity</td>
<td>[31, 33, 34, 37, 40]</td>
</tr>
<tr>
<td>Adipogenic transcriptional factors&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Downregulation</td>
<td>[36, 43, 48, 50-52]</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
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<tr>
<td>Adipogenesis</td>
<td>Suppression of adipocyte differentiation</td>
<td>[48, 50-52]</td>
</tr>
<tr>
<td>Lipogenesis</td>
<td>Downregulation</td>
<td>[29, 31, 33, 35, 36]</td>
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<tr>
<td>(expression and/or activity of lipogenic&lt;sup&gt;d&lt;/sup&gt; enzymes)</td>
<td>Upregulation</td>
<td>[29, 31, 33, 36, 39]</td>
</tr>
<tr>
<td>Lipolysis</td>
<td>Upregulation</td>
<td>[29, 36, 38, 40, 47]</td>
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<tr>
<td>(expression and/or activity of lipolytic&lt;sup&gt;e&lt;/sup&gt; enzymes)</td>
<td></td>
<td></td>
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<tr>
<td>Uncoupling proteins</td>
<td>Upregulation</td>
<td>[29, 36, 38, 40, 47]</td>
</tr>
<tr>
<td>(mRNA and/or protein expression in WAT and BAT)</td>
<td></td>
<td></td>
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</tbody>
</table>

<sup>a</sup> Diabetic/obese KK-A<sup>y</sup> mice or high-fat-fed mice and rats.
<sup>b</sup> Note: an increase in plasma LDL and total cholesterol was observed only in genetically modified diabetic/obese KK-A<sup>y</sup> mice but not in the wild type mice or rats fed a high-fat diet.
<sup>c</sup> Adipogenic transcriptional factors: peroxisome proliferator-activated receptor γ (PPARγ) and CCAAT-enhancer-binding protein (C/EBP) α, β and γ.
<sup>d</sup> Lipogenic enzymes (WAT and/or liver): fatty acid synthase, malic enzyme, glucose-6-phosphate dehydrogenase, glycerol-3-phosphate dehydrogenase, phosphatidate phosphohydrolase, stearoyl-coenzyme A desaturase-1.
<sup>e</sup> Lipolytic enzymes (WAT and/or liver): fatty acid β-oxidation, carnitine palmitoyltransferase, adipose triacylglycerol lipase, hormone-sensitive lipase, lipoprotein lipase.

NS – not significant
Highlights

• Fucoxanthin is a carotenoid derived from brown seaweeds
• Fucoxanthin exerts anti-obesity effects in rodents under a high-fat diet
• Fucoxanthin improves the plasma lipid profile and liver function
• Fucoxanthin is a promising nutritional supplement for treatment of obesity and related pathologies