NEW PERSPECTIVE IN FISHERIES PRODUCT DEVELOPMENT: IMPORTANCE OF SEAWEEDS AS BIOMASS RESOURCES

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ABSTRACT

Brown seaweeds have an important role to preserve coastal ecosystems. Brown seaweeds are also major class for aquacultured seaweeds. They contain valuable nutrients and bioactive components and some of them have not been found in terrestrial plants. Especially, much attention has been paid to brown seaweed lipids because of their high functionality. Several brown seaweeds show high total lipids (TL) contents, ranging from 10-20 wt% per dry weight. The lipids are rich in functional 18:4n-3, 20:5n-3 and 20:4n-6. Brown seaweed TL also contains fucoxanthin as a key functional compound. Brown seaweed lipids show anti-obesity and anti-diabetic effects, which are mainly due to the up-regulatory effect of fucoxanthin on energy expenditure in abdominal white adipose tissue and glucose utilization in muscle.

1. Introduction

People know that marine foods participate in human health promotion. A diet rich in marine products is considered in worldwide to result in lowered incidence of cardiovascular disease, diabetes, cancer and stroke. Although these protective effects are attributed to nutraceuticals contained in marine foods, in most cases, details in the mechanisms of their physiological activities have been unclear or under investigation. In this presentation, I introduce brown seaweed lipids as functional food material, especially focusing on novel marine nutraceutical, fucoxanthin.

Brown seaweed lipids contain many types of bioactive compounds, such as omega-3 polyunsaturated fatty acids (PUFAs), omega-6 arachidonic acid, fucoxanthin, fucosterol and some polyphenols. Among these compounds, fucoxanthin, a major carotenoid in brown seaweeds, is regarded as a nutraceutical compound specific to brown seaweed lipids, as it shows several physiological effects based on unique molecular mechanisms (Miyashita et al., 2011). Therefore, brown seaweed lipids represent a potent functional lipid source. On the other hand, because of the high level of omega-3 PUFAs, such as eicosapentaenoic acid (EPA, 20:5n-3) and stearidonic acid

(SDA, 18:4n-3), brown seaweed lipids may be susceptible to oxidation. In the present study, characteristic oxidative stability of brown seaweed lipids is also discussed.

2. Brown seaweed lipids

Algae can be divided into two groups, macro-algae (seaweeds) and micro-algae. Seaweeds are photosynthetic-like plants that form basic biomass in intertidal zones. There are approximately 10,000 seaweed species, which are broadly classified into three main groups based on their pigmentation: brown (Phaeophyta), red (Rhodophyta) and green (Chlorophyta) seaweeds. As seaweeds lack many of the distinct organs found in terrestrial plants, whole parts are available as a biomass source. Recently, much attention has been paid to seaweeds as effective biomass sources because of their high carbon dioxide absorption rate relative to those of terrestrial plants.

The most abundant food component of seaweeds is non-starch polysaccharides, such as carrageenan and alginate. These substances are not degraded by mammalian enzymes; thus, seaweeds can be regarded as fiber-rich materials (Wong & Cheung, 2003). Seaweeds also biosynthesize fucose-containing sulfated polysaccharides, such as fucoidan, which has been reported to possess a variety of biological activities (Jiao et al. 2011). The quality of seaweed protein is acceptable compared to other diet vegetables, mainly due to its high content of essential amino acids. Recently, seaweed lipids have drawn increased interest due to their several health benefits (Miyashita et al., 2011).

Although seaweeds have significantly lower lipid contents than marine fish, they are still a potential source of functional lipids due to their large stock in coastal waters. While the lipid content in oily fish has been reported to be approximately 20 wt% per dry weight (DW), occasionally reaching 50 wt% per DW, seaweeds may contain up to 1-5 wt% total lipids (TL) per DW (Terasaki et al., 2009). On the other hand, a recent study reported that contents of TL and omega-3 polyunsaturated fatty acids (PUFAs) of seaweeds vary seasonally, indicating that the TL of some Sargassaceae brown seaweeds could reach 15 wt% TL per DW and could contain over 40 wt% omega-3 PUFAs per total fatty acids (Nomura et al., 2013). Ghosh et al. (2012) found TL levels of more than 10 wt % per DW of three tropical brown seaweeds, *Dictyota bartayresii* (11.91±2.00 mg/g DW), *Dictyota dichotoma* (10.80±0.99 wt % per DW) and *Spatoglossum macrodontum* (11.73±0.49 wt % per DW), and two tropical green seaweeds, *Caulerpa sertularioides* (13.04±1.46 wt % per DW) and *Derbesia tenuissima* (12.14±5.9 wt % per DW). High TL contents have also been reported from brown seaweeds collected in tropical areas of the Indian Ocean (7-8 wt % per DW) (Thinakaran et al. 2012) and the Hawaiian coast (16-20 wt % per DW) (McDermid & Stuercke, 2003).

3. Oxidative stability of seaweed lipids

Although the class composition of seaweed lipids also varies by species, geographical location and environmental factors, the glycoglycerolipid (GL) class is most common, consisting of monogalactosyl-diacylglycerols (MGDG), digalactosyl-diacylglycerol (DGDG) and sulfoquinovosyl-diacylglycerol (SQDG). GL usually represented more than half of the TL content. The GL generally contain high levels of omega-3 PUFAs (EPA, SDA) and omega-6 arachidonic acid (20:4n-6, ARA) (Holdt & Kraan, 2011). These omega-3 and omega-6 PUFAs have been known to show several kinds of health beneficial effects. Substantial epidemiological and case-control study data demonstrate the reduction of cardiovascular disease (CVD) risk by the intake of omega-3 PUFAs such as EPA and DHA, which are the active forms of omega-3 PUFAs (Leaf et al., 2008; Wang et al., 2006). The important cardio-protective effect of both omega-3 PUFAs has also been demonstrated by clinical studies (Russo, 2009) and genetic and nutrigenetic approaches (Allayee et al., 2009). Considering an alternate view that humans have a poor ability to form DHA from LNA, American and European heart associations recommend a high intake of longer-chain and more unsaturated forms of LNA, such as EPA and DHA, for the prevention of sudden cardiac death and other cardiovascular dysfunctions (De Backer et al., 2003; Smith et al., 2006).

ARA, the active form of omega-6 PUFA, also plays an important role in biological systems, such as in the immune response, thrombosis and brain function (Hoffman et al., 2009; Le et al., 2009). ARA and DHA are used as supplements in commercial infant formulas because both PUFAs are essential for infant neurodevelopment. ARA and DHA are major constituents of cell membranes and play an important role in the structure of neurons in the central nervous system, where they are present at high concentrations (Davis-Bruno & Tassinari, 2011). The combination of ARA and DHA has also been found to be effective in the improvement of age-related disorders of the brain and cognitive functions (Kiso, 2011).

On the other hand, because of their large number of double bonds, these PUFAs in brown seaweed lipids are very easily oxidized. Oxidative deterioration of these PUFAs is one of the most important problems in food chemistry, as lipid oxidation products cause undesirable flavors and lower the nutritional quality and safety of lipid-containing foods. Although omega-3 and omega-6 PUFAs are thought to be easily oxidized or decomposed, several experimental findings have demonstrated the exceptionally high stability of these PUFAs in brown seaweeds and their products (Sugimura et al., 2012). When dried *Undaria pinnatifida* (wakame), one of the most

popular edible brown seaweeds in Japan, was stored at 50°C, there was a slight decrease in the PUFA content, namely, the SDA, ARA, and EPA contents. There was also no increase in the peroxide values of the extracted lipids after the incubation of the dried material for 210 days at 50°C.

Prabhasankar *et al.* (2009) reported the sensory, chemical and structural properties of cooked pasta containing wakame powder. The heat process involved in pasta preparation (3 h at 75°C) did not oxidize PUFA in the pasta. No oxidation of omega-3 and omega-6 PUFAs of brown seaweed lipids was found in scones, a baked product (Sugimura et al., 2012). Sensory analysis indicated that the sensory scores of scones containing 0.5 wt% and 2 wt% wakame powder were more favorable than those of the control scone without wakame powder.

4. High oxidative stability of PUFAs as GL form

The high oxidative stability of PUFAs in seaweed products will be due to several reasons, namely, presence of antioxidants and physical protection of PUFA oxidation by high molecular compounds such as proteins and polysaccharides. In addition, the recent study showed that PUFAs as GL form, a major lipid class in the seaweed lipids, would be related to their high oxidative stability in seaweeds. The study compared the oxidative stability of purified GL obtained from spinach leaves and brown edible seaweed (*Laminaria japonica*) with those of phosphatidylcholine (PC) from salmon roe lipid and TAG from sardine oil and soybean oil (Yamaguchi et al., 2012). Due to their higher average number of bisallylic positions (-CH=CH-CH_2-CH=CH-), salmon roe PC and sardine oil TAG were oxidized more rapidly than soybean oil TAG. In contrast, spinach GL and brown seaweed GL showed higher oxidative stability than that of soybean oil TAG, although the average number of bisallylic positions of both GLs was much higher than that of soybean oil TAG and almost the same as those found in sardine oil TAG and salmon roe PC. Therefore, PUFAs in GL form may protect against oxidation, which may be related to the defense system against oxidative attack to omega-3 PUFAs in photosynthetic tissue.

Lipid oxidation is most effectively inhibited by the suppression of hydrogen abstraction from a bisallylic position by a free radical. The presence of other molecules near double bonds can protect the bisallylic positions against free radical attack. The higher oxidative stability of PUFAs in GL form may be due to the protective effect of galactosyl and sulfoquinovosyl moieties on PUFAs bonded to the same GL molecule (Yamaguchi et al., 2012).

5. Anti-obesity effect of fucoxanthin

Brown seaweed lipids contain up to 5% fucoxanthin (Terasaki et al., 2009). Fucoxanthin supplementation to the obese-diabetes model mice significantly decreased the body weight gain and abdominal white adipose tissue (WAT) weight compared with the control (Maeda et al., 2005,2007,2009). The decrease of body weight was consistent with that of abdominal WAT weight. Significant decrease in the body weight and the excess fat accumulation in abdominal WAT by fucoxanthin intake were also observed in normal mice fed high fat diet. In addition, comparative study using both obese model KK-A^y mice and lean C57BL/6J mice indicated the specificity of fucoxanthin. Fucoxanthin attenuated the excess fat accumulation in abdominal WAT of obese KK-A^y mice, while no effect was found in lean C57BL/6J mice fed normal-fat diet (Hosokawa et al., 2010). On another hand, feeding of fucoxanthin significantly suppressed abdominal WAT weight of C57BL/6J mice fed high-fat diet to the same level of that found in normal dietary group (Maeda et al., 2009). Furthermore, fucoxanthin supplementation normalized hyper-glycemia, hyperinsulinemia and hyperleptinemia of the mice fed high-fat diet. These results suggest that suppressive effect of fucoxanthin on the WAT weight gain is specific for adiposity in the development of obesity in mice. This specificity will be important for the safe application of fucoxanthin to human obese therapy.

Major target of fucoxanthin will be abdominal WAT, because more than 80% of fucoxanthin metabolites were accumulated in abdominal WAT, when purified fucoxanthin containing diet (100 mg fucoxanthin/100 g diet) was given to mice. Dietary fucoxanthin preferentially accumulates as amarouciaxanthin A in the abdominal WAT and as fucoxanthinol in the other tissues; therefore, the main active form of fucoxanthin in abdominal WAT will be amarousiaxanthin A. Furthermore, molecular level analysis showed the uncoupling protein 1 (UCP1) induction by fucoxanthin as main mechanism for the anti-obesity effect of fucoxanthin.

UCP1 is a major factor of the thermogenic process occurring in BAT (Kozak, 2010; Seale, 2010). The presence of UCP1 allows BAT to dissipate the electrochemical gradient that is normally used to drive adenosine triphosphate synthesis. And then, BAT can generate heat by this uncoupling oxidative phsphorylation. Thermogenic activity of BAT is dependent on UCP1 expression level controlled by the sympathetic nervous system via noradrenaline that is stimulated by cold, adrenergic stimulation, □3-agonists, retinoids and thyroid hormone (Argyropoulos & Harpe, 2002; Mozo et al., 2005; Nedergaard et al., 2001). This signaling pathway includes noradrenaline binding to the

□3-adorenarine receptor (□3Ad) on adipocyte plasma membrane, □3Ad coupling to heterotrimeric G-protein and to adenylyl cyclase, resulting in elevated levels of intracellular cAMP, activation of cAMP-dependent protein kinase (PKA), and of cyclic AMP response element binding protein (CREB). PKA activation induces hormone-sensitive lipase (HSL) expression that stimulates lipolysis and free fatty acids liberated serve as substrate in BAT thermognesis. They also act as cytosolic second messengers which activate UCP1 as peroxisome proliferator-activated receptor-□ (PPAR□ ligand. In addition to PPAR-□, peroxisome proliferator-activated receptor gamma co-activator 1 (PGC-1) will be a key molecule for the thermogenesis in BAT. PGC-1 can bind to a variety of nuclear receptors including the retinoic acid and thyroid hormone receptors, both of which positively regulate expression of UCP-1. Moreover, mitochondrial biogenesis is induced by PGC-1 activation.

When fucoxanthin was fed to mice, BAT weight significantly increased as compared with control mice. Interestingly, the fucoxanthin supplementation also induced UCP1 expression even in abdominal WAT, showing that the decrease in abdominal WAT weight of fucoxanthin intake in rodents would be due to the up-regulation of thermogenesis through UCP1 expression both in BAT and abdominal WAT. UCP1 is mainly expressed in BAT through the up-regulation or stimulation of several key bio-molecules such as □3Ad, PGC-1, and PPAR□as described above. Although UCP1 expression is the signature of BAT, it has been also found in WAT of mice overexpressing forkhead box protein C2 (FoxC2), a winged helix gene, with a change in steady-state levels of several WAT and BAT derives mRNAs (Cederberg et al., 2001). This result suggests the possibility of UCP1 expression even in WAT. Although the mechanism for the UCP1 expression in abdominal WAT by fucoxanthin supplementation has not yet been completely made clear, up-regulation of several factors such as □3Ad and PGC-1 would be a key event for the explanation of the fucoxanthin activity.

6. Other nutritional impact of brown seaweed lipids

Fucoxanthin also improves insulin resistance and decreases blood glucose level through the regulation of adipocytokine secretions from the abdominal WAT (Hosokawa et al., 2010). Another important molecular mechanism for the improvement of glucose utilization by fucoxanthin is glucose transporter 4 (GLUT4) up-regulation and promotion of its translocation to the cell membrane from cytosol (Nishikawa et al., 2012). Therefore, when brown seaweed lipids are given to obesity/diabetes model mice, excess fat accumulation in abdominal WAT is reduced, and glucose levels are restored

to normal levels, mainly due to the presence of fucoxanthin in the lipids (Maeda et al., 2005,2009). This activity of fucoxanthin has been reported to appear at levels of more than 60 mg fucoxanthin intake/kg mouse/day (Airanthi et al., 2011), while a significant reduction of abdominal WAT in obese female volunteers was only observed for fucoxanthin intakes of less than 0.024 mg/kg/day (2.4 mg intake/day for volunteers with 100 kg average weight) (Abidov et al., 2010). The difference in the effectiveness between rodents and humans may be due to different absorption rates and/or different sensitivities to fucoxanthin.

Omega-3 PUFAs can enhance the anti-obesity and anti-diabetic activities of fucoxanthin. The abdominal WAT weight of obese/diabetes model mice fed 0.1% fucoxanthin and 6.9% fish oil containing EPA and DHA has been reported to be significantly lower than that of the mice fed fucoxanthin alone (Maeda et al., 2007). This effect was comparable to that found in mice fed 0.2% fucoxanthin. In addition, a combination diet of 0.1% fucoxanthin and fish oil also markedly decreased the blood glucose and plasma insulin concentrations to the same levels found in 0.2% fucoxanthin supplementation. On the other hand, omega-3 fish oil alone had little effect on abdominal WAT weight and plasma glucose level, indicating the synergistic activity of omega-3 PUFAs on fucoxanthin activity. Because brown seaweed lipids contain high levels of omega-3 PUFAs, the effect of fucoxanthin of the lipids will be greater compared with that of fucoxanthin alone.

A significant increase in DHA and ARA in the liver has been observed after fucoxanthin supplementation to mice, even if the fucoxanthin level of brown seaweed lipids was not high enough to produce anti-obesity and anti-diabetic effects in the mice. (Airanthi et al., 2011). This increase in DHA and ARA could be explained by the up-regulatory effect of fucoxanthin on DHA and ARA biosynthesis (Tsukui et al., 2007,2009). Therefore, when brown seaweed lipids were given to animals, a significant increase in DHA and ARA of the liver was also observed compared with the control (Airanthi et al., 2011). In this case, the high level of omega-3 PUFAs and ARA in brown seaweed lipids will also contribute to the increase in DHA and ARA in the liver. On the other hand, despite the higher levels of ARA and DHA, the lipid peroxidation level in the liver of the mice fed brown seaweed lipids was significantly lower than that in the control mice. An analysis of antioxidant metabolites in the liver indicated the involvement of *in vivo* antioxidant activities of fucoxanthin metabolites (fucoxanthinol and amarousiaxanthin A) (Airanthi et al., 2011; Sachindra et al., 2007).

7. Conclusion

Several brown seaweed families are foundational species, forming underwater forests that provide numerous ecological services to coastal ecosystems. They are regarded as having significant potential to serve as a biomass source. The major nutrients of brown seaweeds are polysaccharides, including undigested fibers, minerals, proteins and lipids. Although the lipid content of brown seaweeds is less than the content of other nutrients, it contains biologically active compounds, such as fucoxanthin, omega-3 EPA and SDA and omega-6 ARA. Among these compounds, fucoxanthin is key to understanding the characteristic functionality of brown seaweed lipids. The oxidative stability of PUFAs is occasionally problematic in the application of marine lipids to food and other products. A recent study indicated the high oxidative stability of omega-3 PUFAs in brown seaweed lipids. Although further study will be needed to confirm this characteristic oxidative stability of PUFAs in brown seaweed lipids, these lipids may be applied to nutraceuticals and functional foods as an oxidatively stable omega-3 source. For the commercial use of brown seaweed lipids, a search for TL-rich seaweed materials will be important.

8. References

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