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海藻活性物质在医药中的潜在应用

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摘 要

海藻富含多糖、蛋白质、脂肪酸、维生素和矿物质等活性物质，具有抗氧化、抗炎、免疫调节、抗凝血、抗肿瘤等多种生物活性，可以用于治疗多种疾病。通过了解海藻的主要生物活性物质及其生物活性研究进展，本文总结了海藻主要活性物质的组成、生物活性和作用机理，为进一步开发和研究海洋资源提供参考。

关键词

海藻，活性分子，生物活性

Potential Applications of Algae Bioactives in Medicine

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Abstract

Algae are rich in bioactive substances such as polysaccharides, proteins, fatty acids, vitamins, and minerals, among other active substances. They have various bioactivities such as antioxidant, anti-inflammatory, immunomodulatory, anticoagulant, and anti-tumor effects, which can be used to treat various diseases. By understanding the main bioactive substances of algae and the progress of their bioactivity research, this paper summarizes the composition, bioactivity, and mechanism of action of the main bioactive substances of algae, providing a reference for further development and research of marine resources.

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Keywords

Algae, Active Molecules, Bioactivity

1. 引言

作为地球上最早的生命形式之一，海藻以其丰富的多样性、广泛的分布范围和众多的数量吸引了科研人员的深入探索。海藻种类众多且结构复杂，根据其色素和结构的不同，可以大致分为三大类：绿藻、红藻和褐藻(见表 1)。由于受到地理、季节和生理变化等多方面因素的影响，不同属和种的海藻所含生物活性化合物的类型和功能呈现出较大的差异。这种多样性直接影响着海藻的价值和应用前景，如图 1 所示，海藻的主要用途包括食品(43.77%)、水凝胶(18.10%)、植物肥料(11.57%)、化妆品(7.86%)、生物塑料(5.34%)以及医药保健品(1.93%)等行业[1]。

Table 1. Seaweed species and their characteristics
表 1. 海藻种类及其特征

种类	数量[2]	特征
绿藻	约 6700 种	绿藻门的海藻主要以叶绿素 a 及 b 为其主要的色素，尤其叶绿素 b 是绿藻独有的色素。大多数也含有黄色色素，这使得其藻体呈绿色。绿藻的结构相对较简单，一般生活在浅海或淡水环境中。在光照充足的环境下，绿藻的光合作用效率很高[3]。
红藻	约 3000 种	红藻门的海藻主要以红藻色素为主，有时还含有黄色和蓝色色素，但很少或不包含绿色叶绿素。因此它们在藻体颜色上表现为红色或紫色。红藻一般生活在深海环境中，因为其独特的色素组合使它们能在低光环境中进行光合作用[4]。
褐藻	约 1800 种	褐藻门的海藻主要以褐藻色素为主，也含有绿色叶绿素 a 和 c。因此，褐藻的藻体颜色为褐色或黄绿色。褐藻的体型通常比红藻、绿藻大很多，甚至有的能成长到几十米长。褐藻一般生活在寒冷的温带海域，尤其是水深、光线弱的环境[5]。

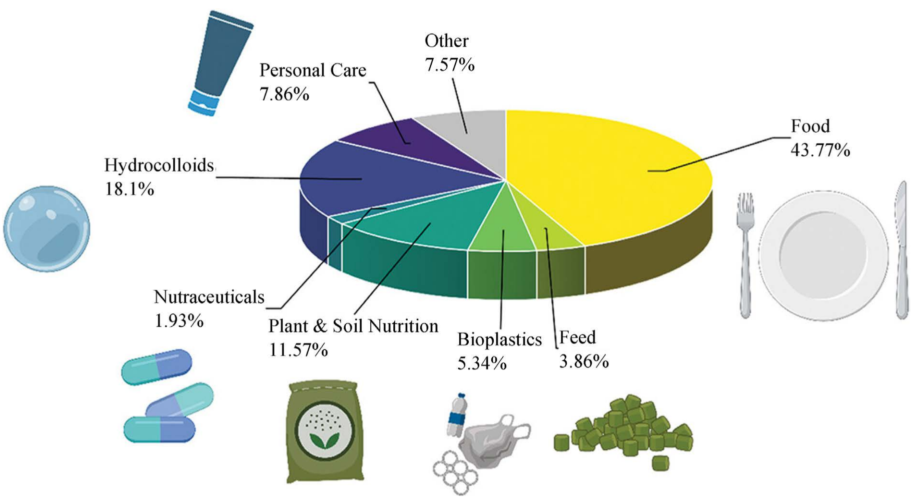

Figure 1. The current application direction of seaweed [1]
图 1. 海藻目前的应用方向[1]

海藻在生态环境中享有独特的生长条件，其含有的天然代谢物质是陆生动植物无法比拟的。如图 2 所示，从功能基团和分子尺寸角度区分，海藻活性物质主要包括多糖、蛋白质、脂肪酸、维生素、矿物质和其他活性物质。这些活性物质存在于藻类的细胞外基质、细胞壁、原生质体，以及细胞内的初次和次级代谢产物中，不仅对海藻自身生理生化过程起着重要作用，同时也具有很高的经济价值和医药开发潜力[6]。

Figure 2. Active substances of seaweed
图 2. 海藻活性物质

在进入本世纪以来，随着天然药物研究的发展，人们对海藻活性物质的研究越来越深入。目前已经发现的海藻活性物质在医药上的应用主要集中在抗肿瘤[7]、抗病毒[8]、抗氧化[9]、抗微生物[10]、抗炎症和免疫调节等方面。许多海藻活性物质的详细作用机制和应用方向仍需要进一步的研究。本文通过总结目前海藻活性物质的应用，有助于充分挖掘海藻的潜在价值，为其在医药领域的应用提供更科学、精准的支持。

2. 海藻多糖

海藻多糖是由多个相同或不同的单糖基团通过糖苷键连接形成的高分子碳水化合物，其含量占到藻类干重的 50%以上。目前已在海藻中发现的重要多糖包括琼脂、海藻酸盐、岩藻多糖和海带多糖等(表 2)。这 x 些海藻多糖表现出多种优异的生物活性，包括抗癌[11] [12]、抗氧化[13]、抗病毒[14] [15] [16] [17]、抗凝血[18]、抗肥胖[19]、免疫调节[20]和抗糖尿病[21]等，具有作为药物来源的巨大潜力。

Table 2. Characteristics of common seaweed polysaccharides
表 2. 常见海藻多糖的特点

种类	特点
琼脂	良好的生物相容性和生物可降解性，可用作药物载体、伤口敷料等
海藻酸盐	具有良好的黏附性、凝胶性和生物相容性，可作为肠道药物的载体，细胞支架等
岩藻多糖	具有多种生物活性，包括抗病毒、抗肿瘤、抗凝血等
海带多糖	良好的膳食纤维，具有强抗氧化性，有调节免疫、抗糖尿病等多种功效

2.1. 琼脂

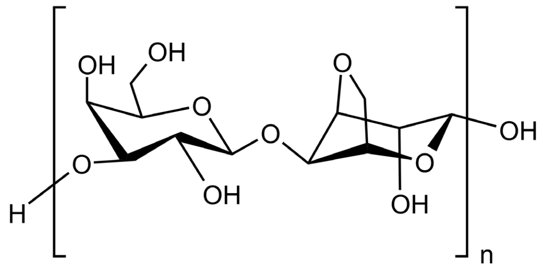

Figure 3. Chemical structure of agar [22]
图 3. 琼脂化学结构[22]

琼脂(Agar) [22]是一种从红藻类植物中提取的多糖物质(图 3)，其结构由两类聚糖分子交替排列构成，即 β-D-半乳糖(A)和 3,6-内醚-L-半乳糖(B)。A 段和 B 段以 α-(1→4)的连接方式交替排列，构成了海藻琼脂的主链，进而形成特殊的三维结构。琼脂广泛用于给药系统，如口服、局部和肠道释放药物制剂。此外，琼脂具有优良的湿润性、生物亲和性，能够治疗烧伤和创伤，促进伤口愈合和皮肤再生[23]。在微生物学领域，琼脂也是重要的固化剂之一，特别是在细菌培养中。琼脂结构特殊不会被细菌分解，细菌可以在其表面生长，以便研究人员对微生物生长特性进行观察。

Zhao [24]等人制备了一系列不同质量比的琼脂/κ-卡拉胶混合水凝胶，结果表明，随着 κ-卡拉胶含量的增加，凝胶强度、温度和凝胶熔化温度均降低，而表观粘度增加。通过添加 κ-卡拉胶可以增强琼脂水凝胶的药物负载效率和持续释放能力，其中释放曲线主要由药物和多糖之间的静电相互作用所主导。Chu [25]等人通过改良琼脂糖的降解时间、增强其不溶性，成功合成出一种创新的琼脂糖–接枝–透明质酸(Ag-g-HA)支架。这种支架利用透明质酸(HA)的生物活性，促进细胞增殖和分泌，从而显著提高伤口愈合速度。并通过巨噬细胞的增殖实验以及动物体内实验，深入验证了 Ag-g-HA 支架在促进伤口愈合方面的生物活性和可行性。

2.2. 海藻酸盐

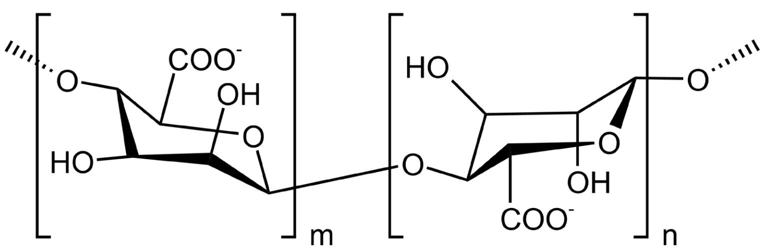

Figure 4. Chemical structure of alginates [26]
图 4. 海藻酸盐的化学结构[26]

海藻酸盐(Alginate) [26]是一种从褐藻类海藻中提取的聚阴离子多糖，其结构主要由甘露醛酸(M)和葡萄醛酸(G)以及其酯化形式构成。这两种醛酸以 1,4-β-D 形式交替排列组成多糖链，每个醛酸单元上的羧基可形成金属盐，钠、钾、钙等常常是附着在其上的金属离子(图 4)。由于其独特的凝胶特性，保水性以及生物相容性，海藻酸盐已广泛应用于医疗领域。在药物输送系统中，海藻酸盐作为微胶囊或纳米粒子，可以有效地保护药物成分不受胃酸破坏，并能在肠道中持续释放，提高药物的吸收率[27]。在伤口治疗方面，海藻酸盐能够提供湿润的环境，有助于伤口的愈合。此外，海藻酸盐胶体还能吸收伤口排泄物，减

少感染的可能，并且在取下敷料时不会对新生的皮肤细胞造成伤害[28] [29] [30]。在组织工程中，海藻酸盐作为三维细胞培养的基质，用于制备人工肝、神经、心脏等组织。海藻酸盐能提供空间结构，促进细胞间的互动，从而有利于细胞生长和分化[31]。

Piyasi [32]等人通过离子交联将槲皮素(QUE)封装到壳心型纳米粒子中，成功制备了槲皮素包封效率高达 95%的藻酸盐–琥珀酸基壳聚糖纳米粒子。该纳米粒子具有显著的 pH 敏感性，能够在体内持续释放槲皮素。相比于糖尿病大鼠口服游离槲皮素，口服槲皮素纳米粒子有明显且持续的降糖效果，进一步证明海藻酸盐纳米载体在糖尿病治疗中的有效性。Lin [33]等人通过湿法纺丝制备出一种大孔结构的海藻酸纤维材料。这种水合海藻酸盐纤维的孔隙大小约为 1 μm，利于细胞代谢物的传输、营养供应和氧气交换，维持包埋细胞的存活。研究结果表明，利用海藻酸纤维支架可以增强神经修复的成功率，并促进胶质细胞和轴突再生，为神经修复提供了有效方法。

2.3. 岩藻多糖

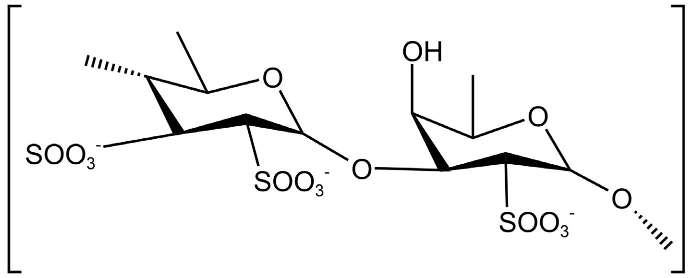

Figure 5. Chemical structure of fucoidan [34]
图 5. 岩藻多糖的化学结构[34]

岩藻多糖(Fucoidan) [34]是一种存在于褐藻中的硫酸化多聚糖，其主要骨架是由岩藻糖和硫酸基团构成，硫酸基团以酯化形式附在岩藻糖上(图 5)。岩藻多糖具有多种生物活性，但其强大的抗凝血作用是迄今为止研究最广泛的。许多研究表明，岩藻多糖的抗凝血活性可能与硫酸集团含量和位置组成有一定关系：硫酸基团含量越高，其抗凝血活性越高[35] [36] [37] [38]。与瞬时抗凝血的肝素相比，天然的岩藻多糖抗凝血效果时间长，对人体的耐受性更好[39]。此外，岩藻多糖可以诱导细胞凋亡来抑制癌细胞生长，将岩藻多糖与其他抗癌药物的结合作为开发抗癌疗法已成为当前海藻医疗研究的焦点[40] [41]。近年来，岩藻多糖在抗病毒研究中的应用日益广泛，特别是针对引发呼吸道感染的流感病毒和冠状病毒。岩藻多糖不仅能在感染前阶段和吸附后阶段灭活病毒颗粒，还可以增强免疫器官[42]。但其结构与抗病毒活性之间的关系还需进一步研究。

Liu [43]等人采用抗溶剂沉淀法，利用玉米醇溶蛋白和岩藻多糖自组装成复合纳米颗粒，用于包封白藜芦醇。该递送系统显示出优异的包封性能、光稳定性、胶体稳定性、释放可控性能。该研究为进一步开发玉米醇–岩藻多糖纳米颗粒作为白藜芦醇或其他疏水性生物活性药物的递送载体奠定了基础。Shanthi [44]小组从绦虫中分离出了具有抗凝性质的岩藻多糖，并将纳米银颗粒(AgNPs)包封在岩藻多糖中。这种纳米颗粒不仅抗凝血能力强，而且对大肠杆菌有良好抑制效果，为新药研发打开了一条途径。

2.4. 海带多糖

海带多糖(laminarin) [45]是由 β-(1,3)-葡聚糖和 β-(1,6)-葡聚糖重复单元构成的线性多糖，其生物活性主要表现在强抗氧化性、免疫调节、抗糖尿病和抗肥胖等方面(图 6)。从大型藻类中提取的海带多糖可以作为化妆品中的天然抗氧化剂使用，Rajauria [46]等人筛选出了具有显著抗氧化能力的海带多糖，证实了

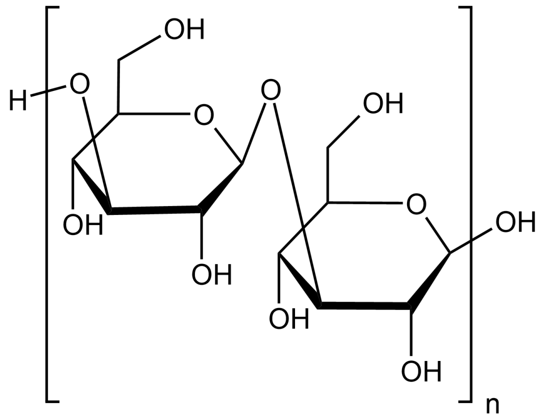

Figure 6. Chemical structure of laminarin [45]
图 6. 海带多糖的化学结构[45]

其对自由基和金属离子的有效清除作用。在免疫调节方面，海带多糖可以与免疫系统的特异性受体相互作用，以实现生物学特性和免疫调节作用。并且海带多糖可以促进 B 细胞和辅助性 T 细胞大量积累来增强免疫系统[47]。在降血糖方面，海带多糖通过抑制碳水化合物水解酶(如 α 淀粉酶和 α-葡萄糖苷酶)，减少葡萄糖亚基的转化，达到降低血糖的效果[48]。Zaharudin [49]等人通过临床统计推断，海带多糖可以改善健康成年人的餐后血糖和食欲控制。Déjean [50]等人的临床研究表明，海带多糖可以影响人体肠道微生物群，从而改善肥胖情况。虽然海带多糖已表现出显著生物活性，但临床试验研究数量有限，仍需进一步进行实验验证。关于其在人体中的安全摄取量，也需要进一步的研究明确。

3. 蛋白质

蛋白质是由一个或多个氨基酸残基长链组成的大生物分子，在人体中起着不可或缺的作用。它们不仅有助于构建和修复人体组织，还能促进代谢反应，协调身体各项功能[51]。海藻蛋白含有丰富的人体必需氨基酸，以及一些特有的蛋白质，如糖蛋白、凝集素、藻胆蛋白，这些蛋白质的结构和功能与海藻的分类、生长环境和代谢途径有关。根据数据统计，红藻的蛋白质浓度通常较高(12.5%~35.2%)，其次是绿藻(9.6%~23.3%)和褐藻(4.5%~16.8%) [52]。许多红藻物种的蛋白质水平与鱼、蛋、谷物和大豆中的蛋白质水平相当[53]。藻类蛋白质作为一种富有潜力的植物蛋白质来源，有望满足人类对健康且可持续的营养需求。

海藻蛋白质大分子具有优异的抗氧化、抗菌、抗炎症、抗高血压、抗糖尿病和抗肿瘤等性质(表 3)。这引起了研究人员对藻类蛋白质及其衍生化合物的重视，尤其是其作为营养保健品、化妆品或药物的潜在应用。虽然已经有关于这些蛋白质和肽的生物活性机制的几种理论，但仍存在许多知识空缺待填补。

Table 3. Bioactive mechanism of seaweed protein
表 3. 海藻蛋白生物活性的作用机制

生物活性	作用机制	参考文献
抗氧化活性	海藻蛋白质及其水解产物能够清除不同类型的自由基，保护细胞免受氧化应激的损伤。这种活性可能与蛋白质的氨基酸组成和构象有关。	[54] [55] [56]
抗菌和抗病毒活性	海藻蛋白质中的凝集素能够特异性地结合细菌、真菌和病毒的细胞壁或膜上的糖基，从而抑制它们的生长和感染。	[57] [58] [59]
降压和抗血栓活性	海藻蛋白质的水解肽能够抑制血管紧张素转换酶和肾素的活性，从而降低血压和预防血栓的形成。这些肽的活性可能与其氨基酸序列和亲水性有关。	[60] [61] [62]
抗癌活性	海藻蛋白质能够诱导肿瘤细胞的凋亡，通过影响细胞周期、DNA 损伤、凋亡相关基因和蛋白的表达，从而抑制肿瘤的生长和转移。	[63] [64]

Continued

抗肥胖活性	海藻蛋白质的水解肽能够抑制消化道中的 α-葡萄糖苷酶和 α-淀粉酶的活性，从而降低血糖水平和糖类的吸收。海藻蛋白质的水解肽也能够抑制二肽基肽酶-IV 的活性，从而增加胰岛素样生长因子-I 受体的信号传导，促进胰岛素的分泌和小肠细胞的增殖和分化。此外，海藻蛋白质的水解肽还能够增加胰高血糖素样肽-1 的水平，从而增强饱腹感，减少能量摄入。	[65] [66] [67]

4. 脂肪酸

脂肪酸是植物或动物的脂溶性部分，是构成脂质的主要元素。根据是否含有双键，又可以分为饱和脂肪酸与不饱和脂肪酸[68]。绿藻、红藻、褐藻和的脂质含量分别在其总质量的 0.2%~15%、0.4%~12%和0.1%~11.5%范围内[1]。海藻中的大部分多不饱和脂肪酸以Omega-3和Omega-6脂肪酸的形式存在[69]。

Omega-3 和 Omega-6 不饱和脂肪酸在生物学中具有诸多重要功能，它们都是细胞膜的重要成分，同时也作为调节血压和炎症反应等生化反应的前体物质[70]。Omega-6 脂肪酸可能引发或加重身体的炎症反应，而 Omega-3 脂肪酸则起到了缓解和抑制炎症的作用。Omega-3 脂肪酸能够有效抑制炎症，降低心血管疾病的风险，并改善大脑功能。在理想情况下，Omega-3 和 Omega-6 脂肪酸的比例应为 1:3~1:5 [71]。

在现代人类饮食中，富含多不饱和脂肪酸的食物，如豆类、种子、谷物等，其含有的是更多的 Omega-6 脂肪酸[72]。因此，为了平衡 Omega-3 与 Omega-6 的比例，有必要增加富含 Omega-3 类不饱和脂肪酸的替代食品摄入量。研究已发现，海藻由于含有丰富的 Omega-3 脂肪酸，有望成为理想膳食营养补充剂[71] [73]。

5. 维生素和矿物质

如表 4 所示，海藻富含多种维生素和矿物质，具有成为优质的膳食营养补充品的潜力。

Table 4. Vitamins and minerals in seaweed
表 4. 海藻中的维生素与矿物质

活性物质	种类	参考文献
维生素	维生素 A，B 族复合维生素(B_1, B_2, B_3, B_5, B_6, B_8, B_9, B_{12})，维生素 C，维生素 D，维生素 E，维生素 K	[74] [75] [76] [77]
矿物质	钠，钾，磷，钙，镁，铁，锌，锰，铜，碘	[71] [74] [78]

6. 其他活性物质

6.1. 藻类多酚

海藻多酚(Algae Polyphenols)是海藻次级代谢产物，在绿藻、红藻、褐藻中均有分布，是海藻保护自身免受植食性动物干扰的有效组分[79]。目前已鉴定出超过 50,000 种不同的多酚分子，所有酚类化合物都含有至少一个或多个可高度聚合的羟基取代基的芳香酚环[80] (图 7)。主要类群为酚酸类、香豆素类、黄酮类、二苯乙烯类、单宁类、木酚素和木质素等[81]。

酚类化合物具有抗氧化、抗炎、抗糖尿病、抗肿瘤、抗高血压、抗过敏、抑制透明质酸酶和蛋白酶等活性[82] [83] [84] [85]。从褐藻提取的酚类衍生物的大多数都表现出显著的抗糖尿病活性，主要通过抑制 α-葡萄糖酶和 α-淀粉酶，改善胰岛素敏感性治疗糖尿病。Park [86]等人研究了 12 种褐藻提取物的抗糖基化作用，对褐藻中已鉴定的酚类化合物的高级糖基化末端(AGE)抑制效果进行了评价，确定其为主要的抑制剂。Nwosu [87]研究了从英国水域常见的四种可食用大型海藻中提取的褐藻多酚对培养结肠癌细

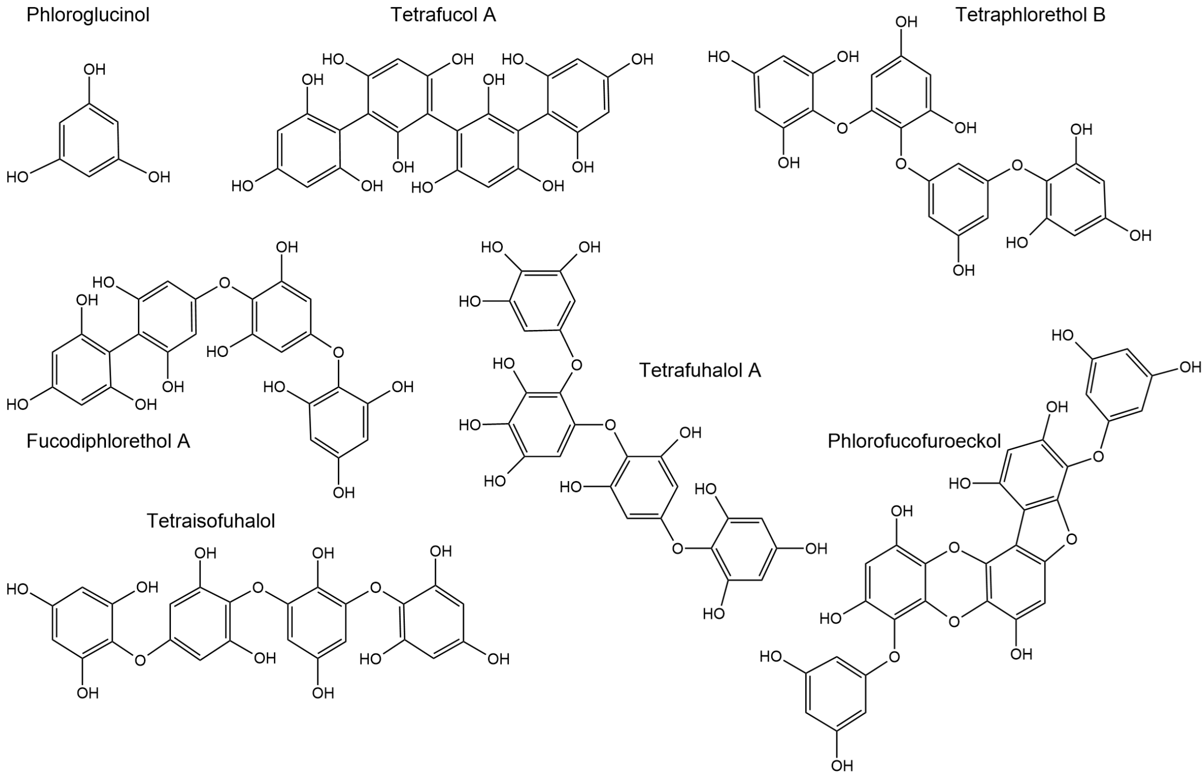

Figure 7. Chemical structures of different types of phlorotannins [80]
图 7. 不同类型褐藻多酚的化学结构[80]

胞和抑制消化酶能力进行了测试。发现四种都能在一定程度上抑制结肠癌细胞和 α-淀粉酶活性。Naveen [88]研究了褐藻酚类物质的抗氧化和抗糖尿病特性，发现其对 α-淀粉酶和 α-葡糖苷酶半抑制浓度(IC50)分别为(47.2 ± 2.9 μg)和(28.8 ± 2.3 μg)，可以用作抗糖尿病药物。

在抗氧化和抗癌方面，Wang [89]等人研究了藻类多酚化合物 dieckol (DK)对可凝结颗粒(CPM)刺激的人体皮肤细胞和斑马鱼体内衰老的影响。结果表明，DK 通过抑制氧化应激和炎症反应，可以有效减缓斑马鱼的衰老。DK 可作为改善 CPM 诱导的皮肤老化治疗剂，或作为药妆和制药行业的活性成分。Faride [90]等人探讨了海藻多酚提取物 ECME 对乳腺癌的防治作用。实验表明，ECME 对雌激素依赖的人乳腺癌细胞 MCF-7 和非雌激素依赖的人乳腺癌细胞 MB-MDA-231 都具有抗增殖作用，且对正常细胞无毒。多酚结构丰富的 ECME 通过诱导凋亡来抑制癌症，降低内源性雌激素的生物合成，从而进一步提升抗氧化状态，具有防治乳腺癌的潜力。

尽管海藻多酚有很多有价值的生物活性，但其在海藻中含量较低，且结构复杂、易氧化等缺点，增加了其纯化的难度[91]。关于海藻多酚的分离纯化及生物活性等方面的研究仍相对较少，限制了海洋多酚类化合物的产业化进程。

6.2. 海藻色素

藻类衍生的天然色素是理想的商业环保材料，广泛用于食品中[92]。在海藻中发现的色素包括叶绿素、叶黄素、藻胆素和胡萝卜素等。它们结构中含有的双键能保护其他分子免受活性自由基诱导的氧化应激[93]。此外，许多研究还证明，海藻色素具有抗癌[94] [95]、抗炎症[96]、保护神经[97]和抗血栓等活性[98]等。如今，研究人员专注于探索用于人体健康的高昂藻类营养品，需要把研究重点转移在用天然色素取代合成色素上。

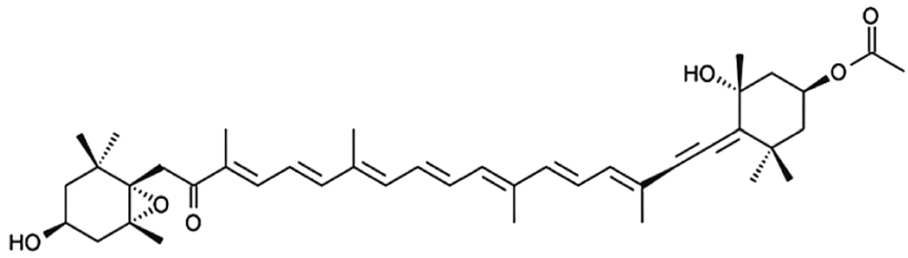

Figure 8. Chemical structure of fucoxanthin [99]
图 8. 岩藻黄质的化学结构[99]

岩藻黄质(Fucoxanthin) (图 8)，作为水生生物中的叶黄素型类胡萝卜素，主要分布在褐藻中并占据了主导位置。它遮盖了其他色素(如叶绿素、胡萝卜素和其它叶黄素)，使海藻显现出棕色至黄色的色调[99]。得益于大型褐藻来源丰富且处理成本低，岩藻黄质占到类胡萝卜素年自然产量的 10%以上[100]。岩藻黄质具有一个烯丙键、5,6-单环氧化物和九个共轭双键。独特的结构使其可以淬灭单线态氧，保护细胞和其他组织结构免受氧化损伤[101]。Liao [102]等人探讨了岩藻黄质对地塞米松诱导的小鼠成肌细胞的影响。结果表明，岩藻黄质能够明显缓解小鼠成肌细胞萎缩。Masashi [103]等人使用小鼠模型和细胞培养系统研究岩藻黄质对白色脂肪组织中炎性脂肪细胞因子的影响，以及其代谢产物岩藻黄质醇对脂肪细胞和巨噬细胞的影响。实验结果表明，岩藻黄质能特异性地抑制糖尿病/肥胖小鼠的脂肪组织重量，并降低白色脂肪组织中促炎脂肪细胞因子的表达。此外，岩藻黄质的代谢物岩藻黄质醇能抑制脂肪细胞和巨噬细胞中的炎症反应。揭示了岩藻黄质和其代谢物岩藻黄质醇可能是一种有效的抗炎和抗糖尿病/肥胖的天然药物，为开发新的抗炎和抗糖尿病/肥胖药物提供了新的思路。

虾青素(Astaxanthin) (图 9)是一种天然类胡萝卜素，广泛存在于水生生物中，如鱼、虾、蟹、藻类和真菌。与法夫酵母(0.4%)、太平洋磷虾(0.012%)、北极虾(0.12%)相比，雨生红球藻含有高达 4%质量比的虾青素[104]。目前市场上 95%的虾青素都是人工合成产物，如表 5 所示，合成虾青素的抗氧化能力是角黄素的 2.7 倍，玉米黄素的 1.6 倍，*β*-胡萝卜素 4.9 倍，叶黄素的 2.6 倍，番茄红素的 1.6 倍，维生素 C 的 6000 倍，白藜芦醇的 3000 倍[105] (表 5)。然而，因其化学残留和立体异构未被批准作为人类膳食补充剂[106]。天然虾青素的单线态氧清除能力是合成虾青素的 55 倍，是迄今为止发现的自然界最强细胞抗氧化剂[107]。

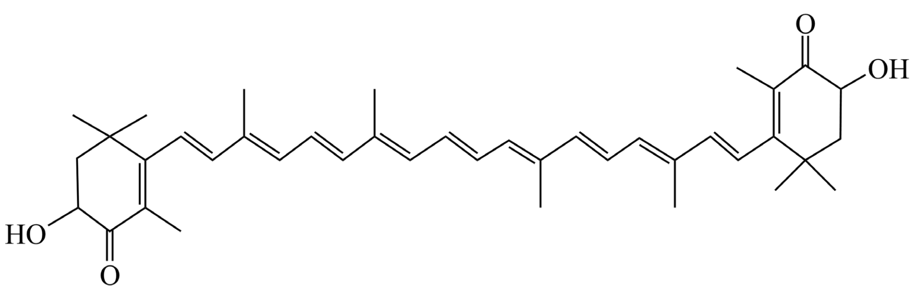

Figure 9. Chemical structure of astaxanthin
图 9. 虾青素的化学结构

Table 5. Total singlet oxygen quenching rate constants [105]
表 5. 单线态氧清除反应常数[105]

物质	测试浓度范围(μM)	反应常数($10^9M^{-1}s^{-1}$)
虾青素	0.01~15	5.4
角黄素	0.01~15	2.0

Continued

α-胡萝卜素	0.01~15	0.93
β-胡萝卜素	0.01~15	1.1
番茄红素	0.01~15	3.4
叶黄素	0.01~15	2.1
玉米黄素	0.01~15	3.4
维生素 C	20~50,000	0.00089
维生素 E	10~20,000	0.049
白藜芦醇	10~10,000	0.0018

目前在欧美地区已经广泛食用天然虾青素作为膳食补充剂，研究人员建议每天最佳摄入量为 4~6 mg [106]。Jean [108]等人采用随机双盲安慰剂对照的方法，将 42 名健康的年轻女性分为三组，每天给予不同量的虾青素，研究膳食虾青素对健康成年女性受试者的生理作用。实验结果表明，天然虾青素在调节人体免疫反应、抑制 DNA 损伤和改善炎症方面具有积极作用。心血管疾病，例如冠心病和高血压，往往与氧化应激和炎症反应有关。虾青素的抗氧化性能可以帮助防止低密度脂蛋白(LDL)的氧化，从而降低动脉硬化的风险[109]。其抗炎性质可以减少体内的炎症反应，降低高血压和心脏病风险[110]。虾青素还能通过防止血小板聚集和抑制凝血因子的激活，来降低血栓风险，进一步防止心脏病发作和中风[111]。

虾青素不溶于水的性质极大地限制了其在生物体内的吸收[112]。研究高效的递送策略是当前主流的方向之一。虾青素在暴露于光线下时，结构会发生改变，导致逐渐退色，抗氧化效果大打折扣。其次，在运输过程中难以保持低温环境，其活性也会有所降低。研究如何提高虾青素的稳定性，延长保存期限，以及在更宽范围的条件下保持其活性和颜色，是目前需要解决的问题。

7. 总结与展望

海藻，作为一种储量丰富且可再生的绿色植物，将成为重要的海洋资源库。据报道，2017 年台湾、中国、日本、德国等微藻生物质生产国每年生产 19,000 吨脱水生物质，营业额为 57 亿美元[113]。如今，海藻养殖体系已趋于成熟，但海藻活性物质的富集与分化提纯还需要进行重大改进和整合，以实现有选择、有目的地利用生物活性物。例如，如何调节海藻生长条件，从而达到富集不同活性物质的效果；如何在提取稳定海藻多糖时，不破坏其他易分解的活性物质，从而解决利用率低的问题；美国 IFF 公司所生产的超纯海藻酸钠是全球唯一商品化的组织工程级海藻酸钠，无菌产品售价高达 800 美元/克，昂贵的售价限制了对该多糖的大规模研究[114]。从微观角度，人体直接食用海藻，其吸收效果差，难以吸收的海藻基质(如膳食纤维)也可能抑制海藻活性物质的肠道吸收[115]。这需要研究人员投入大量的精力开发新的药物递送体系，或将海藻活性物质与现有药物相结合，进一步了解其作用机制及临床效果。

海藻活性化合物未来在医疗领域的应用富含无限可能性。它们能够促进人造器官领域的创新，提供更出色的生物相容性和机械性能。在细胞培养方面，这些化合物可以增强细胞的生物活性和增殖能力，为基础研究及临床治疗提供重要支持。在药物开发方面，基于海藻活性物质有望合成出疑难杂症的特效药。更多的药理活性和潜在应用还需广大科研工作者继续探索。

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