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Vitamin C from Seaweed: A Review Assessing Seaweed as Contributor to Daily Intake

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Abstract: Seaweeds are indiscriminately said to contain significant amounts of vitamin C, but seaweeds are a diverse group, which may limit the ability to generalize. Several studies have been performed on vitamin C in seaweed, and this review covers these findings, and concludes on how much vitamin C is found in seaweeds. A systematic review of vitamin C in 92 seaweed species was conducted followed by analyzing the 132 data entries. The average vitamin C content was 0.773 mg g$^{-1}$ seaweed in dry weight with a 90th percentile of 2.06 mg g$^{-1}$ dry weight. The vitamin C content was evaluated based on taxonomical categories of green, brown and red seaweeds (Chlorophyta (phylum), Phaeophyceae (class), and Rhodophyta (phylum)), and no significant differences were found between them. The vitamin C content was compared to other food sources, and this showed that seaweeds can contribute to the daily vitamin C intake, but are not a rich source. Moreover, seasonal variations, analytical methods, and processing impacts were also evaluated.

Keywords: ascorbic acid; macroalgae; comparison; food; quality; consumption; processing; recommended nutrient intake; dietary reference intake; seasonal variation; analyses; taxonomy

1. Introduction

Humans are unable to synthesize vitamin C (chemically: ascorbic acid, ascorbate). Humans rely on an adequate supply of vitamin C from their diet and it is therefore considered an essential micronutrient [1]. Vitamin C is fully absorbed and distributed in the human body, with the highest concentrations found in the brain, eye, and adrenal gland [2]. It is involved in collagen synthesis, iron metabolism, tissue growth, and vascular functions, as well as biosynthesis of carnitine, and antioxidant reactions such as inhibiting lipid peroxidation [1–3]. Vitamin C is a reductant, meaning it functions as an electron donor and when donating two electrons, it oxidizes into dehydroascorbic acid [1,4]. The vitamin is known for the prevention of scurvy, but may also be able to prevent cardiovascular diseases and some cancer forms [1,2,5]. The Recommended Nutrient Intake (RNI) established by FAO/WHO for vitamin C is 45 mg day$^{-1}$ for adults, which is the amount required to half saturate the body [1]. The Recommended Dietary Allowance (RDA) or Population Reference Intake (PRI) is defined as the average daily level sufficient to meet the nutrient requirements in nearly all healthy individuals. The RDAs established by the Institute for Medicine (U.S.) are 75 and 90 mg day$^{-1}$ for women and men, respectively [6], whereas the PRIs set by EFSA are 95 and 110 mg day$^{-1}$ for women and men, respectively [7]. The Institute for Medicine (2000) describes that smokers dispose of lower vitamin C, even when on a vitamin C rich diet, therefore it is recommended in the United States that the RDA for smokers is increased by 35 mg day$^{-1}$ [6,8].

The Tolerable Upper Intake Level (UL) is not established by the European Food Safety Authorities (EFSA) [9], although the National Institute of Health (USA, NIH) has
established a UL for adults of 2000 mg day\(^{-1}\) [8], as intakes in that ratio have been shown to produce unpleasant diarrhea and abdominal cramps [1,6,8].

Oxidation of ascorbic acid into dehydroascorbic acid occurs easily due to exposure to high pH, high temperatures, light, oxygen, enzymes as well as exposure to the metals Fe\(^{3+}\), Ag\(^{+}\), and Cu\(^{2+}\) [3]. As dehydroascorbic acid also has corresponding biological importance as ascorbic acid it is important to include both compounds in the analysis of the total vitamin C content of the food [3].

Seaweeds are a common part of the diet in some Asian countries, but they are not traditional in the Western diet. There is an increasing commercial demand for seaweed products due to consumer focus on health and functional foods [10,11]. Some seaweeds contain several ingredients and bioactive compounds, that are of commercial interest such as hydrocolloids, minerals, and polyphenols [12,13].

Several peer-reviewed papers state that seaweeds are also a rich source for vitamin C [4,10,14–16] and vitamin C content has been analyzed for various species. More specifically stating that the highest content is found in brown and green algae [17,18] with concentrations of 0.5–3.0 mg g\(^{-1}\) dry weight (dw) and red algae containing between 0.1 and 0.8 mg g\(^{-1}\) dw [15]. Moreover, Munda (1987) stated that some species have sufficient amounts to cover the recommended daily intake for adults [4]. The statements that seaweeds do in fact contain a significant amount of vitamin C is interesting to investigate. First of all, the term “seaweeds” is very broad and diverse. It is not straightforward to conclude on such a broad term, when it consists of more than 10,000 species divided into green, red, and brown seaweed [19]. The chemical composition of seaweeds are therefore very different in regard to carbohydrates for cell walls and storage, amino acid profile, minerals and pigments, and most likely also when it comes to vitamins [13,20,21]. Secondly, to the best of the authors’ knowledge, an overall picture of the vitamin C content in seaweeds has not yet been established in the literature. It is important to clarify which seaweeds, if any, are rich in vitamin C. A method to establish whether seaweed does in fact contain high contents of vitamin C is to compare the content to the dietary reference intakes such as RNI and other food sources. Examples of foods considered rich in vitamin C are citrus fruits, guava, kiwi, mango, and some berry types [1,22].

The review aims to create a collection of peer-reviewed studies and clarify the vitamin C content of various seaweed species. The data entries from the collection are assessed, evaluated by statistical analysis, and compared with metadata. The influence of processing on the vitamin C content is highlighted, and the method of analysis will be discussed in brief. Lastly, concluding whether seaweed can contribute as a vitamin C source at all or is a rich source of vitamin C compared to other foods.

2. Materials and Methods

The work is a systematic review with a meta-analysis performed on the data collected. A thorough search of several studies related to vitamin C in seaweed were identified and collected. Statistical techniques were applied to the data collected to examine and interpret the pooled data to understand the general picture of the vitamin C content in seaweed.

2.1. Literature Search

Relevant literature was collected in the period of August to November 2020 from the following databases; Scopus, Web of Science, and the internal university library database DTU Findit. The following keywords and combinations thereof were used: “Vitamin C OR Ascorbic acid”, “Vitamin C content OR Ascorbic acid content” and “seaweed OR macroalgae”. The titles and abstracts were assessed individually for their relevance. If the literature was not available online, the local university library requested and collected scans of the papers.

The sources were collected in Mendeley (Elsevier) and duplicates were removed. The initial criteria for inclusion were; peer-reviewed journals, books, or reports written in English, Norwegian, Danish, or German language. All sources but one (Norwegian) were
written in English. Moreover, a criterion for inclusion was that the unit of vitamin C should be expressed in dry weight (dw). Although, in the case where the unit was given in wet weight (ww) or 100 g edible portion, the water content should also be given or achieved from contacting the authors, so a calculation to dry weight was possible.

As the taxonomical names of the seaweed species are updated regularly, the species names were updated to the current official name found in AlgaeBase [19]. The update of the names can be found in the supplementary material.

2.2. Data Collection and Meta-Analysis

For the literature review of vitamin C, 34 studies on seaweed were found relevant with a total of 132 inputs. The means and standard deviations from the papers were collected. Some metadata categories were chosen for the review tables; taxonomical order, harvest method, collection site, season, year of harvest, sample treatment, replicates (n), and analytical method. In the situations where the research focus of the paper was to study the effect of season or processing, the means from their analyses were kept apart and entered individually. These metadata categories are provided, so an individual assessment of the relevance and reliability of each data entry can be assessed by the reader. In the case of missing metadata, the study was still included in the review. If the unit was not indicated for vitamin C content, the study was excluded from the review. In the analysis of taxonomical categories as well as the comparison to other food sources, all data were included. It is important to be critical to this approach, as some processing might have influenced the vitamin C content, but it was not possible to make a valid objective decision of excluding specific data points, so all data with the correct unit was included. Even though the replicates were given from some of the different studies, each entry in the review tables weighted \( n = 1 \), when evaluating the data.

It was not possible to conclude on each individual species, as only one or few entries from each species were found in the literature. Therefore, the species were divided into taxonomical categories of green (G), brown (B), and red (R) seaweeds (Chlorophyta (phylum), Phaeophyceae (class), and Rhodophyta (phylum)) as well as taxonomical orders. This was to be able to make a representative overview of their specific vitamin C content.

For data analysis, visualization, and statistics the software program R [23] was used. Statistical analyses were boxplots with mean, median, standard deviations, minimum, and maximum. Moreover in the cases where statistically significant differences were interesting a one-way ANOVA with a Tukey post hoc test was applied. Means were considered significantly different when \( p < 0.05 \).

3. Results and Discussion

3.1. Taxonomical Analysis

Vitamin C content is shown in Tables 1–3 for a total of 92 species (Phaeophyceae; 36, Rhodophyta; 33 and Chlorophyta; 23). The vitamin C content is given in mg g\(^{-1}\) dw. This unit was chosen, as the sample treatment before analysis were different among the papers.
Table 1. Vitamin C in Phaeophyceae (Class). Species arranged by orders.

| Species                        | Wild/ Cultivated | Origin               | Sample Treatment                                      | n  | Analytical Method          | Vitamin C mg g⁻¹ ± SD | Reference |
|--------------------------------|------------------|----------------------|-------------------------------------------------------|----|---------------------------|------------------------|-----------|
| **Dictyotales**                |                  |                      |                                                       |    |                           |                        |           |
| Dictyota dichotoma             | Wild             | Piran, Slovenia      | January–November 1984                                  | 8  | Spectrophotometrically     | 3.79 ± 0.44            | [4]       |
| Padina gymnospora              | Wild             | Tanjung Tuan, Malaysia | - 2008 ***                                       | -  | Titration                 | 0.085                  | [24]      |
| Padina gymnospora              | Wild             | Hurghada, Egypt      | April–June 2019                                       | 1  | Chromatography             | 0.006                  | [25]      |
| Padina pavonica                | Wild             | Piran, Slovenia      | October–November 1984                                 | 2  | Spectrophotometrically     | 0.58 ± 0.26            | [4]       |
| Padina tetrastromatica         | Wild             | Visakhapatnam, India | Yearly 1996–1997                                      | 12 | Spectrophotometrically     | 0.525                  | [26]      |
| **Ectocarpales**               |                  |                      |                                                       |    |                           |                        |           |
| Ectocarpus siliculosus         | Wild             | Piran, Slovenia      | January–June 1984                                     | 5  | Spectrophotometrically     | 2.52 ± 0.58            | [4]       |
| Mesogloia vermiculata          | Wild             | Piran, Slovenia      | April 1984                                            | 1  | Spectrophotometrically     | 3.10                   | [4]       |
| Scytosiphon lomentaria         | Wild             | Piran, Slovenia      | January–May 1984                                      | 4  | Spectrophotometrically     | 2.00 ± 0.26            | [4]       |
| **Fucales**                    |                  |                      |                                                       |    |                           |                        |           |
| Ascoyphyllum nodosum           | Wild             | -                    | - 1920                                                | -  | -                         | 0.55–1.65              | [27]      |
| Ascoyphyllum nodosum           | -                | -                    | - -                                                    | -  | -                         | 0.082                  | [28]      |
| Carpodocapsa crinita           | Wild             | Piran, Slovenia      | March–November 1984                                   | 5  | Spectrophotometrically     | 1.62 ± 0.28            | [4]       |
| Cystosiphon compressa          | Wild             | Piran, Slovenia      | January–November 1984                                 | 9  | Spectrophotometrically     | 2.13 ± 0.28            | [4]       |
| Durvillaea antarctica          | Wild             | Santa Ana, Chile     | October–December 2012                                 | 3  | Chromatography             | 0.348                  | [29]      |
Table 1. Cont.

| Species                | Origin                          | Sample Treatment | n  | Analytical Method | Vitamin C mg g⁻¹ ± SD | Reference |
|------------------------|---------------------------------|-----------------|----|-------------------|------------------------|-----------|
| **Dictyotales**        |                                 |                 |    |                   |                        |           |
| *Fucus vesiculosus*    | Wild Chincoteague Island, USA   | Freeze-dried    | -  | Chromatography    | 0.517 ± 0.078          | [30]      |
|                        | Wild Chincoteague Island, USA   |                 |    |                   | 0.409 ± 0.101          | [30]      |
| *Fucus virsoides*      | Wild Piran, Slovenia            | Vacuum-dried    | 9  | Spectrophotometrically | 2.66 ± 0.45          | [4]       |
| *Himanthalia elongata* | Wild Galicia, Spain             | Fresh           | 2  | Chromatography    | 2.92 ± 0.37 **         | [31]      |
|                        | Bought Galicia, Spain           | Dehydrated      | 6  | Chromatography    | 0.207 ± 0.09           | [32]      |
|                        | Wild Galicia, Spain             | Dried < 38 °C   | 3  | Chromatography    | 0.692 ± 0.053          | [33]      |
| *Polycenia myrica*     | Wild Hurghada, Egypt            | Washed with tap and distilled water, air-dried | 1  | Chromatography    | 0.008                  | [25]      |
| *Sargassum baccularia* | Wild Tanjung Tuan, Malaysia     | -               |    | Titration         | 0.224                  | [24]      |
| *Sargassum cervicorne* | Wild Tanjung Tuan, Malaysia     | -               |    | Titration         | 0.254                  | [24]      |
| *Sargassum hemiphyllum*| Wild Tung Ping Chau, Hong Kong  | Washed then sun-dried for 4 days | 3  | Titration         | 0.519 ± 0.035          | [18]      |
|                        | Wild Tung Ping Chau, Hong Kong  | Washed then oven dried for 15 h at 60 °C | 3  | Titration         | 0.977 ± 0.121          | [18]      |
| *Sargassum hemiphyllum*| Wild Tung Ping Chau, Hong Kong  | Washed then freeze-dried | 3  | Titration         | 1.53 ± 0.12            | [18]      |
| *Sargassum latifolium* | Wild Hurghada, Egypt            | Washed with tap and distilled water, air-dried | 1  | Chromatography    | 0.007                  | [25]      |
| *Sargassum meclurei*   | Wild Nha Trang, Vietnam         | -               | 1  | -                 | 0.657 **               | [34]      |
### Table 1. Cont.

| Species                          | Origin                  | Sample Treatment | n  | Analytical Method | Vitamin C mg g⁻¹ ± SD | Reference |
|---------------------------------|-------------------------|------------------|----|-------------------|------------------------|-----------|
| **Dictyotales**                 |                         |                  |    |                   |                        |           |
| *Sargassum muticum*             | Wild Bourgneuf Bay, France | Fresh            | -  | Chromatography    | 0.560 ± 0.000         | [35]      |
| *Sargassum muticum*             | Wild Hurghada, Egypt    | Washed with tap and distilled water, air-dried | 1  | Chromatography    | 0.012 ± 0.000         | [25]      |
| *Sargassum polycystum*          | - Kota Kinabalu, Malaysia | Washed with distilled water | 3  | Titration         | 0.383 ± 0.000 **      | [36]      |
| *Sargassum spp.*                | Wild Hurghada, Egypt    | Washed with tap and distilled water, air-dried | 1  | Chromatography    | 0.004 ± 0.000         | [25]      |
| *Sargassum tenerium*            | Wild Visakhapatnam, India | Washed in fresh water and freeze-dried | 11 | Spectrophotometrically | 0.280 ± 0.000         | [26]      |
| *Sargassum vulgare*             | Wild Visakhapatnam, India | Washed in fresh water and freeze-dried | 1  | Spectrophotometrically | 0.300 ± 0.000         | [26]      |
| *Turbinaria conoides*           | Wild Tanjung Tuan, Malaysia | Washed in running water | -  | Titration         | 0.112 ± 0.000         | [24]      |
| *Turbinaria spp.*               | Wild Hurghada, Egypt    | Washed with tap and distilled water, air-dried | 1  | Chromatography    | 0.008 ± 0.000         | [25]      |
| **Laminariales**                |                         |                  |    |                   |                        |           |
| *Alaria spp.*                   | - -                     | -                | -  | -                 | 0.0221–0.497 ± 0.007  | [37]      |
| *Eisenia arborea*               | Wild Bahia Asunción, Mexico | Sun-dried        | 10 | Chromatography    | 0.344 ± 0.06 ± 0.07   | [38]      |
| *Laminaria digitata*            | - -                     | -                | -  | -                 | 0.355 ± 0.000         | [28]      |
| *Laminaria ochroleuca*          | Wild Galicia, Spain     | Dried < 38 °C    | 3  | Chromatography    | 0.785 ± 0.092 ± 0.07  | [33]      |
| *Laminaria spp.*                | Wild Redondela, Spain   | Fresh            | 6  | Chromatography    | 0.096 ± 0.004 ** ± 0.007 | [31]      |
| *Saccharina latissima*          | Wild Damariscotta Bay, USA | Washed in running water | 3  | Titration         | 0.611 ± 0.074 ± 0.02  | [40]      |
Table 1. Cont.

| Species            | Origin                          | Sample Treatment | n  | Analytical Method | Vitamin C mg g⁻¹ ± SD | Reference |
|--------------------|---------------------------------|------------------|----|-------------------|------------------------|-----------|
| **Dictyotales**    |                                 |                  |    |                   |                        |           |
| *Dictyotales*      |                                 |                  |    |                   |                        |           |
| Saccharina latissima | Cultivated                   | Damariscotta Bay, USA | May and June 2017 | Washed in running water and dried in various ways | 16 | Titration | 0.104 ± 0.016 ** | [40] |
| Undaria pinnatifida | Wild                          | Redondela, Spain | February 2011 | Fresh | 6 | Chromatography | 0.118 ± 0.022 | [39] |
| Undaria pinnatifida | Wild                          | Redondela, Spain | February 2011 | Boiling 20 min. | 6 | Chromatography | nd | [39] |
| Undaria pinnatifida | Wild                          | Galicia, Spain   | December 2015 | Dried < 38 °C | 3 | Chromatography | 0.693 ± 0.090 | [33] |
| Undaria pinnatifida | Bought                        | -                | 2008 *** | - | - | Titration | 0.030 | [24] |
| *Sphacelariales*   |                                 |                  |    |                   |                        |           |
| *Sphacelariales*   |                                 |                  |    |                   |                        |           |
| Halopteris scopari | Wild                          | Piran, Slovenia | January–November 1984 | Vacuum-dried at 30 °C | 9 | Spectrophotometrically | 2.04 ± 0.48 | [4] |

* mg ascorbic acid per g dry weight; ** mean of given numbers on various drying methods with no significant differences; *** year of publication, year of harvest not given; nd, not detected
| Species                      | Origin                                      | Sample Treatment                                                                 | n  | Analytical Method   | Vitamin C mg g\(^{-1}\) ± SD | Reference |
|------------------------------|---------------------------------------------|----------------------------------------------------------------------------------|----|---------------------|--------------------------------|-----------|
| **Bangiales**                |                                             |                                                                                  |    |                     |                                |           |
| Nori                         | Bought                                      | Washed in running water, freeze-dried                                          | -  | Titration           | 0.390                          | [24]      |
| Pyropia acanthophora         | Wild Central West Coast, India              | Washed in seawater, shade dried                                                 | 5  | Chromatography      | 0.042 ± 0.019                  | [41]      |
| Pyropia columbina            | Wild Brighton, New Zealand and Dunedin, New Zealand June–October 1986 | Washed with seawater and oven-dried at 30 °C                                   | 7  | Chromatography      | 2.62 ± 0.68                    | [42]      |
| Porphyra spp. Porphyra umbilicalis Porphyra umbilicalis | Wild Galicia, Spain December 2014 Dried < 38 °C |                                                                                  | 3  | Chromatography      | 0.712 ± 0.102                  | [33]      |
| Porphyra umbilicalis         | Wild Galicia, Spain - 2010 Fresh            |                                                                                  | 2  | Chromatography      | 1.05 ± 0.27 **                 | [31]      |
| **Ceramiales**               |                                             |                                                                                  |    |                     |                                |           |
| Centroceras clavulatum       | Wild Visakhapatnam, India Yearly 1996–1997 | Washed in fresh water and freeze-dried                                          | 1  | Spectrophotometrically | 0.345                      | [26]      |
| Ceramium ciliatum            | Wild Piran, Slovenia March–June 1984        | Vacuum-dried at 30 °C                                                           | 4  | Spectrophotometrically | 3.19 ± 0.51                 | [4]       |
| Halopithys incurva           | Wild Piran, Slovenia January–November 1984  | Vacuum-dried at 30 °C                                                           | 9  | Spectrophotometrically | 1.13 ± 0.24                | [4]       |
| Laurencia obtusa             | Wild Khanh Hoa, Vietnam July 2003           |                                                                                  | 1  | Spectrophotometrically | 0.252**                    | [34]      |
| Nitophyllum punctatum        | Wild Piran, Slovenia April 1984             | Vacuum-dried at 30 °C                                                           | 1  | Spectrophotometrically | 2.62                        | [4]       |
| **Corallinales**             |                                             |                                                                                  |    |                     |                                |           |
| Amphiroa fragilissima        | Wild Visakhapatnam, India Yearly 1996–1997 | Washed in fresh water and freeze-dried                                          | 11 | Spectrophotometrically | 0.285                       | [26]      |
Table 2. Cont.

| Species          | Origin                          | Sample Treatment                                                                 | n    | Analytical Method | Vitamin C mg g⁻¹ ± SD | Reference |
|------------------|---------------------------------|----------------------------------------------------------------------------------|------|-------------------|------------------------|-----------|
| **Bangiales**    |                                 |                                                                                  |      |                   |                        |           |
| Nori             | Bought                          | Washed in running water, freeze-dried                                           | -    | Titration         | 0.390 ± SD            | [24]      |
| Jania rubens     | Wild                            | Vacuum-dried at 30 °C                                                            | 1    | Spectrophotometrically | 0.436 ± SD          | [4]       |
| Jania rubens     | Wild                            | Washed in fresh water and freeze-dried                                          | 1    | Spectrophotometrically | 0.310 ± SD          | [26]      |
| **Erythropeltales** |                                |                                                                                  |      |                   |                        |           |
| Pyrophyllon subtumens | Wild | Washed with seawater and oven-dried at 30 °C                                      | 4    | Chromatography    | 2.32 ± 0.33           | [42]      |
| **Gelidiales**   |                                 |                                                                                  |      |                   |                        |           |
| Gelidiella acerosa | Wild | Khanh Hoa, Vietnam                                                                | 1    | -                 | 0.522 ± SD            | [34]      |
| Gelidium pusillum | Wild | Visakhapatnam, India                                                              | 2    | Spectrophotometrically | 0.150 ± SD          | [26]      |
| Millerella myriocladia | Wild | Visakhapatnam, India                                                               | 1    | Spectrophotometrically | 0.185 ± SD          | [26]      |
| Pterocladia heteroplatos | Wild | Visakhapatnam, India                                                               | 11   | Spectrophotometrically | 0.175 ± SD          | [26]      |
| **Gigartinales** |                                 |                                                                                  |      |                   |                        |           |
| Callophyllis variegata | Wild | Washed in deionized water and dried at 20 °C                                      | 3    | Chromatography    | 0.011 ± SD            | [29]      |
| Chondrus crispus  | Wild                            | Dried < 38 °C                                                                    | 3    | Chromatography    | 0.538 ± 0.055         | [33]      |
| Species                          | Origin                          | Sample Treatment                                                                 | n  | Analytical Method | Vitamin C mg g⁻¹ ± SD | Reference |
|---------------------------------|---------------------------------|-----------------------------------------------------------------------------------|----|-------------------|------------------------|-----------|
| *Eucheuma denticulatum*         | Cultivated, Sulawesi, Indonesia | Washed with distilled water and dried                                             | 2  | Titration         | 0.035 ± 0.006          | [43]      |
|                                 | Wild, O’ahu, USA                | Washed in filtered seawater and dried at 60 °C in an air oven                    | 1  | Chromatography    | 2.0                    | [44]      |
| *Hypnea musciformis*            | Wild, Visakhapatnam, India      | Washed in fresh water and freeze-dried                                            | 9  | Spectrophotometrically | 0.370          | [26]      |
| *Hypnea valentiae*              | Wild, Nha Trang, Vietnam        | Washed with distilled water                                                        | 1  | -                 | 0.438 **               | [34]      |
| *Kappaphycus alvarezii*         | Cultivated, Bangi Sabah, Malaysia | Washed with distilled water and dried                                             | 3  | Titration         | 0.395 ± 0.000 **       | [36]      |
|                                 | Cultivated, Popayato, Indonesia | Washed in distilled water and dried                                               | 2  | Titration         | 0.033 ± 0.001          | [45]      |
|                                 | Wild, Khanh Hoa, Vietnam        | Washed with distilled water                                                        | 1  | -                 | 0.551 **               | [34]      |
|                                 | Cultivated, Sulawesi, Indonesia | Washed in tap water and dried                                                      | 2  | Titration         | 0.036 ± 0.006          | [43]      |
|                                 | Wild, West Coast, India         | Washed with distilled water and dried                                             | 3  | Chromatography    | 0.107 ± 0.30           | [46]      |
|                                 | Cultivated, Sulawesi, Indonesia | Washed in distilled water and dried                                               | 2  | Titration         | 0.035 ± 0.006          | [43]      |
| *Sphaerococcus coronopifolius*  | Wild, Marmara, Turkey           | Washed in tap water and dried at room temperature                                 | 4  | Titration         | 0.78 ± 0.07            | [47]      |
Table 2. Cont.

| Species                  | Origin                        | Sample Treatment                                                                 | n  | Analytical Method | Vitamin C mg g\(^{-1}\) ± SD | Reference |
|--------------------------|-------------------------------|----------------------------------------------------------------------------------|----|-------------------|-----------------------------|-----------|
| **Gracilariales**        |                               |                                                                                  |    |                   |                             |           |
| *Crassiphycus changii*   | Wild, Tanjung Tuan, Malaysia  | Washed in running water                                                          | -  | Titration         | 0.285                       | [24]      |
| *Crassiphycus changii*   | Cultivated, Kedah, Malaysia  | Washed in running water                                                          | 3  | Titration         | 0.285 **                    | [48]      |
| *Crassiphycus changii*   | Wild, Santubong, Malaysia     | Washed with distilled water and freeze-dried                                    | 3  | Chromatography    | 0.025 ± 0.002               | [49]      |
| *Gracilaria corticata*   | Wild, Visakhapatnam, India    | Washed in fresh water and freeze-dried                                           | 12 | Spectrophotometrically | 0.100                       | [26]      |
| *Gracilaria gracilis*    | Wild, Marmara, Turkey         | Washed in fresh water and freeze-dried at room temperature                      | 4  | Titration         | 0.24 ± 0.01                 | [47]      |
| *Gracilaria tenuistipitata* | Wild, Nha Trang, Vietnam     | Washed in fresh water, shade dried                                               | 1  | -                 | 0.502 **                    | [34]      |
| *Hydropuntia edulis*     | Wild, Thondi, India           | Washed in fresh water, shade dried                                               | 2  | Chromatography    | 5.01 ± 0.40                 | [50]      |
| **Nemariales**           |                               |                                                                                  |    |                   |                             |           |
| *Liagora albicans*       | Wild, Visakhapatnam, India    | Washed in fresh water and freeze-dried                                           | 1  | Spectrophotometrically | 0.155                       | [26]      |
| **Palmariales**          |                               |                                                                                  |    |                   |                             |           |
| *Dulse*                  | Bought                        |                                                                                  |    | Titration         | 0.120                       | [24]      |
| *Palmaria palmata*       | Wild, Galicia, Spain          |                                                                                  | 2  | Chromatography    | 0.039 ± 0.001 **           | [31]      |
| *Palmaria palmata*       | Wild, Bretagne, France        | Dried < 38 °C                                                                    | 3  | Chromatography    | 0.538 ± 0.055               | [33]      |

* mg ascorbic acid per g dry weight; ** calculated from wet weight to dry weight based on given proximate composition; *** year of publication, year of harvest not given; nd, not detected.
Table 3. Vitamin C in Chlorophyta (phylum). Species arranged by orders.

| Species                  | Origin                          | Sample Treatment                                      | n   | Analytical Method  | C Vitamin mg g\(^{-1}\) ± SD |
|--------------------------|---------------------------------|-------------------------------------------------------|-----|--------------------|-------------------------------|
| **Bryopsidales**         |                                 |                                                       |     |                    |                               |
| *Bryopsis pennata*       | Wild Visakhapatnam, India       | Washed in fresh water and freeze-dried                 | 4   | Spectrophotometrically | 0.250                         |
| *Caulerpa lentillifera*  | Wild Tanjung Tuan, Malaysia     | Washed in running water                               | -   | Titration           | 0.274                         |
| *Caulerpa lentillifera*  | Wild BanLam, Thailand           | Washed in running water                               | 3   | Titration           | 0.013 **                      |
| *Caulerpa lentillifera*  | Wild Semporna, Malaysia         | Washed with distilled water                           | 3   | Titration           | 0.389 ± 0.000 **              |
| *Caulerpa racemosa*      | Wild Visakhapatnam, India       | Washed in fresh water and freeze-dried                 | 9   | Spectrophotometrically | 0.275                         |
| *Caulerpa racemosa*      | Wild Khanh Hoa, Vietnam         | -                                                     | 1   | -                  | 0.912 **                      |
| *Caulerpa sertularioides*| Wild Visakhapatnam, India       | Washed in fresh water and freeze-dried                 | 4   | Spectrophotometrically | 0.375                         |
| *Caulerpa taxifolia*     | Wild Visakhapatnam, India       | Washed in fresh water and freeze-dried                 | 7   | Spectrophotometrically | 0.390                         |
| *Codium tomentosum*      | Wild Marmara, Turkey            | Washed in tap water and dried at room temperature     | 4   | Titration           | 1.38 ± 0.19                   |
| *Codium vermilara*       | Wild Piran, Slovenia            | Vacuum-dried at 30 °C                                  | 1   | Spectrophotometrically | 1.00                          |
| Species                  | Origin                        | Sample Treatment                                      | n  | Analytical Method          | C Vitamin mg g⁻¹ ± SD | Reference |
|-------------------------|-------------------------------|-------------------------------------------------------|----|---------------------------|------------------------|-----------|
| **Cladophorales**       |                               |                                                       |    |                           |                        |           |
| *Chaetomorpha antennina*| Wild Visakhapatnam, India     | Washed in fresh water and freeze-dried                 | 9  | Spectrophotometrically     | 0.490 ± SD             | [26]      |
| *Chaetomorpha brachygona*| Wild Visakhapatnam, India     | Washed in fresh water and freeze-dried                 | 8  | Spectrophotometrically     | 0.225 ± SD             | [26]      |
| *Cladophora rupestris*  | Wild Piran, Slovenia           | Vacuum-dried at 30 °C washed in fresh water and freeze-dried | 1  | Spectrophotometrically     | 1.06 ± SD              | [4]       |
| *Cladophora socialis*   | Wild Visakhapatnam, India     | Washed in fresh water and freeze-dried                 | 2  | Spectrophotometrically     | 0.340 ± SD             | [26]      |
| *Cladophora spp.*       | Wild Visakhapatnam, India     | Washed in fresh water and freeze-dried                 | 1  | Spectrophotometrically     | 0.675 ± SD             | [26]      |
| **Ulotrichales**        |                               |                                                       |    |                           |                        |           |
| *Acrosiphonia orientalis*| Wild Visakhapatnam, India     | Washed in fresh water and freeze-dried                 | 12 | Spectrophotometrically     | 0.500 ± SD             | [26]      |
| *Gayralia oxysperma*    | Wild Hawai’i, USA              | Washed in fresh water and freeze-dried                 | 1  | Chromatography             | 1.3 ± SD               | [44]      |
| *Monostroma nitidum*    | Wild Nha Trang, Vietnam        | Washed in fresh water and freeze-dried                 | 1  | Spectrophotometrically     | 0.495 ± SD             | [34]      |
| **Ulva**                |                               |                                                       |    |                           |                        |           |
| *Ulva compressa*        | Wild Visakhapatnam, India     | Washed in fresh water and freeze-dried                 | 6  | Spectrophotometrically     | 0.310 ± SD             | [26]      |
| Species          | Origin                  | Sample Treatment                                                                 | n  | Analytical Method | C Vitamin mg g\(^{-1}\) ± SD | Reference |
|------------------|-------------------------|----------------------------------------------------------------------------------|----|-------------------|-----------------------------|-----------|
| *Ulva flexuosa*  | Wild O’ahu, USA         | Washed in filtered seawater and dried at 60 °C in an air oven                    | 1  | Chromatography    | 3.0                         | [44]      |
| *Ulva intestinalis* | Wild Mu˘ gla, Turkey     | Washed in fresh water, frozen, thawed, dried at 40 °C for 24 hrs                | 3  | Chromatography    | 0.028 ± 0.001               | [52]      |
| *Ulva intestinalis* | Wild Mu˘ gla, Turkey     | Washed in fresh water, frozen, thawed, dried at 40 °C for 24 hrs                | 3  | Chromatography    | 0.034 ± 0.000               | [52]      |
| *Ulva intestinalis* | Wild Mu˘ gla, Turkey     | Washed in fresh water, frozen, thawed, dried at 40 °C for 24 hrs                | 3  | Chromatography    | 0.026 ± 0.000               | [52]      |
| *Ulva intestinalis* | Wild Mu˘ gla, Turkey     | Washed in fresh water, frozen, thawed, dried at 40 °C for 24 hrs                | 3  | Chromatography    | 1.47 ± 0.02                 | [52]      |
| *Ulva lactuca*   | Wild O’ahu, USA         | Washed in filtered seawater and dried at 60 °C in an air oven                    | 1  | Chromatography    | 2.2                         | [44]      |
| *Ulva lactuca*   | Wild Visakhapatnam, India | Washed in fresh water and freeze-dried                                            | 12 | Spectrophotometrically | 0.155                      | [26]      |
| *Ulva reticulata* | Wild Nha Trang, Vietnam | -                                                                               | 1  | -                 | 0.971 **                    | [34]      |
| *Ulva reticulata* | Wild Pattani Bay, Thailand | Washed in running water                                                           | 3  | Titration         | 0.00 **                     | [51]      |
| Species          | Wild/Cultivated | Collection Site          | Season          | Year       | Sample Treatment                                      | n   | Analytical Method | C Vitamin mg g\(^{-1}\) ± SD | Reference |
|------------------|-----------------|--------------------------|-----------------|------------|-------------------------------------------------------|-----|-------------------|-------------------------------|-----------|
| Ulva rigida      | Wild            | Marmara, Turkey          | June            | 2009       | Washed in tap water and dried at room temperature     | 4   | Titration         | 2.05 ± 0.33                   | [47]      |
| Ulva rigida      | Wild            | Northern Adriatic        | January–November| 1984      | Vacuum-dried at 30 °C                                 | 9   | Spectrophotometrically | 2.00 ± 0.52                  | [4]       |
| Ulva rigida      | Wild            | Northwest Iberian coast, Spain | - | 2010 *** | -                                                      | 3   | Chromatography    | 0.942                         | [53]      |
| Ulva spp.        | Wild            | Piran, Slovenia          | January–May     | 1984       | Vacuum-dried at 30 °C                                 | 4   | Spectrophotometrically | 2.04 ± 0.34                  | [4]       |
| Ulva spp.        | Wild            | Piran, Slovenia          | October–November| 1984      | Vacuum-dried at 30 °C                                 | 2   | Spectrophotometrically | 1.23 ± 0.35                  | [4]       |
| Ulva spp.        | Wild            | Visakhapatnam, India     | Yearly          | 1996–1997 | Washed in fresh water and freeze-dried                 | 1   | Spectrophotometrically | 0.420                        | [26]      |
| Ulva spp.        | Wild            | Locquirec, France        | June–September  | 1982      | Rinsed with seawater                                  | 5   | -                 | 0.247 ± 0.278 **             | [54]      |
| Ulva spp.        | Wild            | Galicia, Spain           | December        | 2015       | Dried < 38 °C                                         | 3   | Chromatography    | 0.746 ± 0.136                 | [33]      |

* mg ascorbic acid per g dry weight; ** calculated from wet weight to dry weight based on given proximate composition; *** year of publication, year of harvest not given nd, not detected.
The average content of vitamin C in seaweed from the reviewed studies is 0.773 mg g\(^{-1}\) dw. Boxplots for each taxonomical category are seen in Figure 1. The mean for each category is Chlorophyta; 0.781, Phaeophyceae; 0.815, and Rhodophyta; 0.720 mg g\(^{-1}\) dw. The range, mean and median of the three categories are not varying considerably, thus no significant differences were found between the categories (one-way ANOVA; \(p = 0.882, F = 0.126\)). These results are not taking any of the metadata into consideration. The ranges found in this review for each category were broad, and for Rhodophyta the maximum content found was 5.01 mg g\(^{-1}\) dw.

**Figure 1.** Data analysis of vitamin C content (mg g\(^{-1}\) dw) represented in boxplots and statistical output for the three categories; Chlorophyta (phylum), Phaeophyceae (class), and Rhodophyta (phylum).

The five species with the highest content of vitamin C (above 3.00 mg g\(^{-1}\) dw) were *Hydrodictyon edulis* (R) > *Dictyota dichotoma* (B) > *Ceramium ciliatum* (R) > *Mesogloia vermiculata* (B) > *Ulva flexuosa* (G) and the 90th percentile of the data entries contained 2.06 mg g\(^{-1}\) dw. Their content is comparable to the amount found in peas. Common for the five species is that only one study is published for each of the species, meaning their reliability is not powerful. Data for each individual species are scarce, which is why the seaweed species were divided into the presented categories of green, brown, and red seaweeds. In addition, the entries showed a large variation among species and therefore a broad picture. Looking into the taxonomical order instead of the species, a more reliable and specific estimate of vitamin C content can be achieved.

In Figures 2–4, a boxplot for each represented order is shown. No significant differences were found between the orders of Chlorophyta. It can however be seen that seaweeds within the order *Ulvales* (G) have a wide range reaching up to 3.00 mg g\(^{-1}\) dw. This indicates that *Ulva* are richer in vitamin C compared to other green seaweeds. For the orders within the class Phaeophyceae, a statistically significant difference was found (one-way ANOVA; \(p = 0.005, F = 4.334\)) with a Tukey post-hoc test showing the differences. The statistical results can be found in Figure 3. The order *Ectocarpales* (B) had a high mean of 2.54 mg g\(^{-1}\) dw, but all seaweeds within this order was from the same study. To confirm if *Ectocarpales* are high in vitamin C, other studies should look into species within this order. The orders *Fucales* (B) and *Laminariales* (B) have the lowest content of vitamin C within the Phaeophyceae. This is interesting as some of these brown species (*Alaria esculenta, Ascophyllum nodosum, Fucus vesiculosus, Laminaria spp., Saccharina spp., Sargassum spp., and Undaria pinnatifida*) are of commercial interest [10,11,37,55–58] and probably useful to avoid claiming they are rich in vitamin C. For Rhodophyta no significance was found between orders, although a broad range was seen for the *Ceramiales* (R). It is worth mentioning that the meta-analysis only considers the taxonomical orders, all other metadata that can influence the vitamin C content such as processing are not included in this analysis.
3.2. Comparison to other Foods and RNI

Vitamin C is known to be abundant in rose hips, black and red currants, strawberries, parsley, oranges, and grapefruit [1,59]. In Table 4 the content of vitamin C can be seen for various terrestrial fruits regarded as foods, and the content of seaweeds found in this review. The amount needed to reach the recommended nutrient intake (RNI) is also given as a method to compare the foods and seaweeds. The dietary reference intake RNI is chosen to compare to, as it is an established value set by FAO/WHO on a global evaluation. Other types of dietary reference intakes exist, and those set by EFSA and the Institute of Medicine are all higher and gender-based. This means, that more food production is needed to reach
the levels. It is understood by the authors that the RNI is created to consider the entire diet, but it is simply used for comparison between foods.

Table 4. Vitamin C content found in other food sources as well as these reviewed data categorized on different levels of the taxonomy. Moreover, the amount that is assumed necessary to consume to meet the RNI. All the contents from other foods are calculated based on [22]. The list is made in descending order with seaweeds shaded in the color of the seaweed categories.

| Food            | mg Vitamin C g\(^{-1}\) dw | g ww to Meet RNI; 45 mg Day\(^{-1}\) |
|-----------------|----------------------------|-------------------------------------|
| Rosehip         | 36.4                       | 5.35                                |
| Parsley         | 20.8                       | 14.6                                |
| Broccoli        | 10.1                       | 40.1                                |
| Black currant   | 8.66                       | 24.9                                |
| Strawberry      | 6.67                       | 67.5                                |
| Grapefruit      | 4.08                       | 95.1                                |
| Ectocarpales *  | 2.54                       | 118                                 |
| Peas            | 2.11                       | 105                                 |
| 90th percentile seaweed * | 2.06                     | 146                                 |
| Potato          | 1.29                       | 170                                 |
| Iceberg lettuce | 1.17                       | 818                                 |
| Dictyotales *   | 0.997                      | 301                                 |
| Chlorophyta *   | 0.781                      | 384                                 |
| Average seaweed * | 0.773                    | 388                                 |
| Rhodophyta *    | 0.720                      | 417                                 |
| Fucales *       | 0.686                      | 437                                 |
| Laminariales *  | 0.496                      | 605                                 |

* the amount needed of macroalgae (g ww) calculated based on the assumption of a moisture content of 85% ww. Brown, Phaeophyceae; grey, seaweed in general; green, Chlorophyta; red, Rhodophyta.

Rosehip has a high vitamin C content compared to other foods, and to meet the RNI, less than 6 g of rosehip is needed, whereas for seaweed about 400 g is needed based on wet weight. This is half the amount compared to iceberg lettuce, which shows that seaweeds are a better source of vitamin C compared to iceberg lettuce. Although species within the division Rhodophyta and the orders of Fucales (B) and Laminariales (B) on average contain less than the average of all seaweed species and thereby more than 400 g ww is needed to be consumed to achieve the RNI. It was mentioned that consuming 2–3 g day\(^{-1}\) of vitamin C can cause diarrhea [1], but to reach that more than 5 kg ww seaweed should be consumed. It can be concluded based on the reviewed literature that in general seaweeds are not an abundant source of vitamin C for food consumption. Although some can contribute to the daily intake and assist to achieve the RNI, whereas others only have a minimal contribution. Moreover, these results also indicate, that stating either that seaweeds have a fairly high content of vitamin C, or that they have a low content is difficult. “Seaweed” is undiscriminating, and is a category of a large variety of macroalgal species, but the species variation can be significant and therefore conclusions should be made on the level of e.g., taxonomical divisions, order, or species and not on “seaweed”.

3.3. Seasonal Variation

Three studies looked into the seasonal variation of vitamin C for the species of brown; *Saccharina latissima, Fucus vesiculosus*, and green; *Ulva intestinalis and Enteromorpha spp.* [4,30,40,52]. They all found that the highest content of vitamin C was around April–May, with all seaweeds collected in the Northern Hemisphere. It points towards those seasonal fluctuations of vitamin C that occur in seaweed species. Škrováneková (2011) suggests that seaweeds growing closer to the water surface level will contain higher levels of vitamin C than seaweeds harvested from deep waters [17]. This may be due to the higher antioxidant level needed for the seaweed when exposed to high levels of sun, which fits the results seen for seasonal variation.
3.4. Analytical Method for Vitamin C

Various analytical methods exist to analyze the vitamin C content in food. The reviewed studies can be divided into three categories. Spectrophotometric methods by reducing cupric ions [4,26], titration with 2,6-dichlorophenolindophenol (Titration) [18,24,36,40,43,45,47,48,51], and chromatography such as High Performance Liquid Chromatography (HPLC) [25,29–33,35,38,39,41,42,44,46,49,50,52,53]. Five papers did not mention the analytical method used [27,28,34,37,54].

It is worth to mention that indophenol titration is the official AOAC Method 967.21 for juices [60,61], although many studies on vitamin C in foodstuff are performed by chromatographic methods [3], which is the AOAC First Action Official Method 2012.22 for infant formula and nutritional formulas [62]. No studies referred to the AOAC 984.26-1985, Vitamin C (Total) in Food-Semiautomated Fluor [63].

Quantification of vitamin C by different analytical methods with the same samples was not performed by any study, and it was therefore not possible to conclude the effect of the analytical method. In the case where two or more studies had analyzed the same species with different analytical methods, no specific trend was found such as one analysis always quantifying a higher content. The results, therefore, indicate that even though one analysis might be over- or underestimating, other factors such as biological variations, season, harvest site, sample treatment or other unknown factors can influence the result as well.

3.5. Processing and the Influence on Vitamin C

Vitamin C is somewhat easily degraded, and in nutrient stability studies in foods, it is assumed that if vitamin C is well retained, then other nutrients will be just as well retained if not better. The degradation of vitamin C depends on moisture-, oxygen, light, and metal ion catalysis as well as temperature and pH [5,64]. An analysis of the metadata of processing was performed in this present review (data not shown). No trend for washing methods or drying methods was observed. Therefore it was not possible to conclude the effect of processing on vitamin C in seaweed based on the overall reviewed literature.

A few studies looked into the degradation of vitamin C [18,39,40]. Both Sappati et al. (2019) and Chan et al. (1997) found that sun drying and oven drying at temperatures between 30 and 70 °C had a significant, negative influence on the vitamin C content in Saccharina latissima (B) and Sargassum hemiphyllum (B), respectively. Vegetable blanching and boiling can be performed to reduce microbial load and inactivate enzymes, but it is known that it also compromises quality compounds such as vitamin C [65,66]. Amorim et al. (2012) studied the influence of 20 min. boiling on Undaria pinnatifida (B) and found the reduction of vitamin C to be below the detection limit [39]. Amorim-Carrilho et al. (2014) studied different processing methods on Himanthalia elongata (B). They found that 15 min boiling in 100 °C water, rehydration in water for 10 min, and steaming for 40 min reduced the vitamin C content below the detectable limit [32].

Friedlander (1989) found that seven months of storage decreased the initial value of ascorbic acid in Pyrophyllon subtumens (R) and Pyropia columbina (R) to 15% and 34%, respectively [42]. Some vegetables can lose up to 70% of the initial content during storage [19]. Balan et al. (2016) suggested that a matrix with a fibrous texture and low water content would preserve ascorbic acid better during storage [66], which could be an interesting hypothesis for dried seaweed. Friedlander (1989) also found that drying at 30 °C for 4 h did not affect the ascorbic acid content, moreover did washing or toasting for 15 s of nori sheets not influence the ascorbic acid content.

Although no studies looked into the effect of cutting the seaweed biomass, a study on rose hips showed that cutting would lead to a decrease in vitamin C content, which might also be the case for seaweeds [64].
4. Conclusions

Seaweeds are not a rich source of vitamin C, but when consumed they feed into the daily intake. To reach the Recommended Nutrient Intake approximately 400 g ww of seaweed should be consumed per day, which in contrast to rosehip is 5.35 g ww.

The vitamin C content can vary, due to biological, seasonal, locational, and treatment variations. Moreover, evaluating and generalizing seaweeds can be difficult, the nutritional quality should be evaluated based on e.g., taxonomical category, order, or species. The mean content in seaweed is 0.773 mg g\(^{-1}\) dw with a 90 percentile of 2.06 mg g\(^{-1}\) dw. A study of the taxonomical orders of the species indicated that the green seaweeds Ulvales contained up to 3.00 mg g\(^{-1}\). Whereas, brown species within the orders Fucales and Laminarales had low amounts of vitamin C.

It was found that drying, boiling and long storage time lead to a decrease in vitamin C in seaweed, as it is easily oxidized.

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