



Evaluating food quality of *Arthrospira platensis* for culturing *Daphnia magna*

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Received: 4 August 2023 / Accepted: 11 November 2023 / Published online: 2 December 2023
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Abstract

Arthrospira is a filamentous cyanobacterium, rich in proteins and bioactive compounds, which is a dietary supplement for humans and animals. However, the contribution of this “superfood” on the life history traits of zooplankton is poorly addressed. We conducted *Daphnia magna* growth experiment using *Arthrospira platensis* comparing it with *Chlamydomonas reinhardtii* as quality food, to evaluate the nutritional adequacy of *A. platensis* for rearing daphnids. The trichomes of *A. platensis* was fragmented using a bead crusher for easier ingestion by the daphnids. The growth experiments revealed that *A. platensis* alone did not support both survival and growth of *D. magna*, but the daphnid survival increased after the addition of 20% *C. reinhardtii*. When *A. platensis* was supplemented with 50% and more of *C. reinhardtii*, however, growth was better than to those daphnids exclusively fed on *C. reinhardtii*. This suggests that *A. platensis* have some nutritional limitations essential for daphnids survival and growth instead of less digestibility or toxicity. Carbon (C) to Phosphorus (P) ratio (C:P=46) of *A. platensis* was far below the threshold for daphnid growth (C:P=116). This implies that P limitation is unlikely in *A. platensis* as feed for daphnids. Although the lack of some essential biochemicals such as sterols and polyunsaturated fatty acids may be a more plausible explanation, a small addition of *A. platensis* to standard microalgal foods would result in better growth of zooplankton, including *D. magna*.

Keywords *Arthrospira platensis* · *Daphnia magna* · Essential biochemicals · Food quality

Handling Editor: Ronan Sulpice

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Introduction

Daphnia is a keystone zooplankton, transferring energy and carbon (C) from primary producers to higher trophic levels (Urabe et al. 1997; Martin-Creuzburg et al. 2005; Freese and Martin-Creuzburg 2013). It is a non-selective suspension feeder which consumes various phytoplankton including cyanobacteria and bacteria regardless of their nutritional quality (Fink et al. 2011; Freese and Martin-Creuzburg 2013; Bednarska et al. 2014; Wenzel et al. 2021). Previous studies have revealed the inadequate food quality of cyanobacteria for supporting the growth and reproduction of crustacean zooplankton because of their poor manageability, toxicity, and lack of or an insufficient quantity of essential dietary materials such as polyunsaturated fatty acids (PUFAs) and sterols (von Elert 2002; Wacker and Martin-Creuzburg 2012; Thomas et al. 2022).

Cyanobacteria is poorly ingested by zooplankton because of the long trichome or colonial nature of their cells (von Elert 2002; Bednarska et al. 2014; Thomas et al. 2022). *Daphnia* efficiently consumes food particles in the intermediate size range of 0.3–40 μm , but not those over ca. 50 μm (Geller and Müller 1981; Porter and McDonough 1984; Urabe et al. 1996). Long filamentous algae are too large for daphnids to ingest, and such large food items interfere with the collection of other foods, and consequently cause loss of fitness (Bednarska et al. 2014).

On the other hand, C transfer from cyanobacteria to daphnids can be constrained by elemental limitations; for example, shortage of phosphorus (P) for daphnid growth happens when the C to P ratio in the diet exceeds 300 (Urabe et al. 1997, 2018; Gulati and Demott 1997). Higher P allocation into ribosomal RNA is required to support fast protein synthesis, which explains the direct relationship between growth and P availability in the food (Elser et al. 2003; Bukovinszky et al. 2012). The effect of P limitation in the life history traits of zooplankton depends on the developmental stages and taxa (Thomas et al. 2022). In *Daphnia*, P limitation is pronounced at both growth and reproduction stages (Hartnett 2019), which makes it a crucial element in the food. In addition, the availability of P affects the relative importance of fatty acids in the diet (Gulati and Demott 1997; Thomas et al. 2022).

Even though most cyanobacteria show such food quality constraints in supporting zooplankton life history traits, some cyanobacterial species have outstanding nutritional profiles and provide substantial benefits for humans and animals. *Arthrospira* is a filamentous cyanobacteria that is rich in proteins and bioactive compounds (Martins et al. 2021; Spínola et al. 2022). Its nutritional quality has been widely investigated and used as a food supplement for humans and animals, and in pharmaceutical products (Gentscheva et al. 2023). Its high levels of proteins (60–70%), essential amino acids, fatty acids, and carbohydrates have attracted attention to it as a sustainable food source for humans (Wang et al. 2021) and animals (Altmann and Rosenau 2022). It also has anticancer, antibacterial, antifungal, and antiviral activities because of its phycocyanin, phycocyanobilin, and allophycocyanin production (Nuhu 2013; Wang et al. 2021).

Arthrospira can be cultured using the anaerobically digested effluent (ADE) of organic wastes (Dunn et al. 2013; Hultberg et al. 2017; Matos et al. 2021) and aquatic weeds (O'Sullivan et al. 2010; Kimura et al. 2019). Water hyacinth (*Eichhornia crassipes*), for example, is an invasive aquatic weed that has deleterious effects on various aquatic ecosystems worldwide (Williams 2004; Villamagna and Murphy 2010). In our ongoing project, *Arthrospira* is cultured using ADE produced from over-growing water hyacinth in Lake Tana, Ethiopia (Dersseh et al. 2019; Damtie et al. 2022a, b). Utilizing the *Arthrospira*

produced from the ADE of water hyacinth to culture zooplankton, and then to culture fish using the zooplankton as feed, may be an appropriate way to maximize use of water hyacinth. However, there is limited information on the effects of *Arthrospira* on the growth and reproduction of zooplankton including daphnids. In this study, we conducted a *D. magna* growth experiment using *A. platensis* as a single food and in combination with *C. reinhardtii* to evaluate the food quality of *A. platensis* to rear *D. magna*.

Methods

Microalgae cultivation

A. platensis (NIES-39) and *C. reinhardtii* (NIES-2235) were cultured using SOT medium (Ogawa and Terui 1970) and C medium (Ichimura 1971), respectively (Table 1). Both *A. platensis* and *C. reinhardtii* were grown in 1-L flasks under a photoperiod of 12 D:12 L with light intensity of ca. 440 $\mu\text{mol photons m}^{-2} \text{s}^{-1}$ at 25 °C and ca. 180 $\mu\text{mol photons m}^{-2} \text{s}^{-1}$ at 20 °C, respectively. The algae were harvested at the exponential growth phase and concentrated through centrifugation (4200 g). An aliquot of the algal suspension was collected from the well-mixed algal culture, and the absorbance of the algal suspension was measured with a spectrophotometer (SP-300, OPTIMA®, Tokyo, Japan) at a wavelength of 680 nm. The carbon concentration of the algal suspension was estimated from a regression equation between absorbance and the carbon mass of the cells established before the experiment. A new inoculation for the microalgal culture was made every 5 days for *A. platensis* and every 7 days for *C. reinhardtii* to provide a constant supply of fresh algal food throughout the experiment.

Table 1 Chemical compositions of SOT and C media

SOT medium		C medium	
Chemicals	Concentration (mg/L)	Chemicals	Concentration (mg/L)
NaHCO ₃	16,800	Ca(NO ₃) ₂ ·4H ₂ O	150
K ₂ HPO ₄	500	KNO ₃	100
NaNO ₃	2500	β-Na ₂ glycerophosphate·5H ₂ O	50
K ₂ SO ₄	1000	MgSO ₄ ·7H ₂ O	40
NaCl	1000	Vitamin B ₁₂	0.0001
MgSO ₄ ·7H ₂ O	200	Biotin	0.0001
CaCl ₂	40	Thiamine HCl	0.01
FeSO ₄ ·7H ₂ O	10	Tris (hydroxymethyl) aminomethane	500
Na ₂ EDTA·2H ₂ O	80	Na ₂ EDTA·2H ₂ O	3
H ₃ BO ₃	2.86	FeCl ₃ ·6H ₂ O	0.588
MnSO ₄ ·7H ₂ O	2.5	MnCl ₂ ·4H ₂ O	0.108
ZnSO ₄ ·7H ₂ O	0.222	ZnSO ₄ ·7H ₂ O	0.066
CuSO ₄ ·5H ₂ O	0.079	CoCl ₂ ·6H ₂ O	0.012
Na ₂ MoO ₄ ·2H ₂ O	0.021	Na ₂ MoO ₄ ·2H ₂ O	0.0075

Fragmentation of *A. platensis* trichome

The size of untreated *A. platensis* trichomes ranges from 50 to 500 μm (Wan et al. 2021), which is too large for daphnids to ingest (Geller and Müller 1981; Wenzel et al. 2012; Bednarska et al. 2014). To be easily ingested by the daphnids, *A. platensis* trichomes were fragmented with a bead crusher ($\mu\text{T-01}$, TAITEC). A 2-mL conical screw cap microtube (1392-200-C, WATSON) and zirconia beads (CZS0060, AS ONE Corporation) with a diameter of 0.4–0.6 mm were used to fragment the trichomes. Approximately one-third of the volume of the microtube was filled with zirconia beads, and the remaining volume was filled with an *A. platensis* suspension with concentration of 0.5–0.8 mg C mL^{-1} . The shaking speed of the bead crusher was set at 4600 rpm for 5–25 s. The fragmented *A. platensis* cells were checked by a microscope every 5 s, and the sizes of the trichomes were measured with a digital micrometer (Wraycam, NF500) under inverted microscope (Olympus, IX70) at a magnification of 20 \times .

Growth experiment in *D. magna*

A stock culture of *D. magna* was maintained in aged and filtered tap water (ATW) with a glass fiber filter (Whatman, GF/F, diameter, 47 mm) at 20 °C, photoperiod of 12 L:12 D and light intensity of ca. 180 $\mu\text{mol photons m}^{-2} \text{s}^{-1}$ with sufficient amounts of *C. reinhardtii* ($> 10^5$ cells mL^{-1}). For each food treatment, arbitrarily sorted five neonates born within 12 h from a stock culture were transferred to a 200-mL glass jar filled with ATW and an algal food suspension. The food treatments were conducted at five different ratios of fragmented *A. platensis*:*C. reinhardtii* (100:0, 80:20, 50:50, 20:80, and 0:100) at a food concentration of 4 mg C L^{-1} (Table 2). The *A. platensis* trichomes used for this experiment was fragmented for 25 s. Control treatments exclusively using *C. reinhardtii* as the food algae were conducted at 20%, 50%, and 80% of 4 mg C L^{-1} (Table 2).

The experimental animals were transferred to new bottle containing fresh food and culturing water every day, and dead animals were recorded. All treatments were made in triplicate and lasted for 6 days. At the end of the experiment, the surviving animals from each treatment were collected from the jar, washed with ATW, transferred to a tin capsule, dried in an oven (DV-600, YAMATO) for 24 h, and then weighed on a digital balance with a minimum weighing value of 1 μg (AD-4212D-32, A&D Instruments

Table 2 Food treatments at different supply ratios of *Arthrospira platensis* to *Chlamydomonas reinhardtii* (AP:CR) for *Daphnia magna* growth experiments at food concentration of 4 mg C L^{-1}

Food treatment (AP:CR)	Carbon mass of food (mg C L^{-1})
<i>A. platensis</i> alone (100:0)	4
80% <i>A. platensis</i> + 20% <i>C. reinhardtii</i> (80:20)	3.2 + 0.8
50% <i>A. platensis</i> + 50% <i>C. reinhardtii</i> (50:50)	2 + 2
20% <i>A. platensis</i> + 80% <i>C. reinhardtii</i> (20:80)	0.8 + 3.2
<i>C. reinhardtii</i> alone (0:100)	4
<i>C. reinhardtii</i> alone (0:80)	3.2
<i>C. reinhardtii</i> alone (0:50)	2
<i>C. reinhardtii</i> alone (0:20)	0.8
No food	0

Ltd). In addition, 30 neonates born within 12 h were arbitrarily sorted from a stock culture, and the same procedure described above was carried out to determine the initial dry weight of the animals. Somatic growth rates (g) of the animals were calculated as the increment of the dry mass between newborn (M_0) and 6-day-old animals (M_6) using Eq. (1):

$$g = \frac{\ln M_6 - \ln M_0}{6} \quad (1)$$

Elemental analysis of microalgae

To determine the elemental composition of C, nitrogen (N), and P of the microalgae, we took an aliquot of approximately 10–15 mL of the fresh algal suspension, equivalent to a dry weight of 9.1 ± 0.4 mg for *A. platensis* and 2.9 ± 0.16 mg for *C. reinhardtii* and filtered with a pre-combusted and pre-weighed glass fiber filter (GF/F, diameter, 47 mm, Whatman). The filtered microalgae were dried in an oven (DV-600, YAMATO) at 60 °C for 24 h and weighed on an electronic balance (AW220, SHIMADZU). C and N contents of the algal cells were determined with an NC analyzer (NCH-22 A, SUMIGRAPH). The P contents were determined with an autoanalyzer (Bran+Luebbe, AACS II, Norderstedt, Germany) after degrading the sample with potassium peroxodisulfate at a maximum absorbance wavelength of 880 nm, based on the phosphomolybdenum blue method (Murphy and Riley 1962).

Statistical analysis

Differences in the somatic growth rates of daphnids among the food treatments were tested with one-way analysis of variance (ANOVA). Treatments with no surviving animal per beaker were excluded from the ANOVA. When the ANOVA showed a significant difference, Tukey's honestly significant difference (HSD) test was conducted at $p < 0.05$. All statistical analyses were made using R statistical software (R Core Team 2022).

Results

Trichome sizes of *A. platensis*

Trichome sizes of untreated *A. platensis* ranged from 64 to 595 μm with an average size of 363 μm . These are too large for daphnid ingestion. To ease consumption, the trichomes were fragmented with a bead crusher at the speed of 4600 rpm for different lengths of time (Figs. 1 and 2). This efficiently reduced the trichome to 50 μm on average in 5 s. The fragmented *A. platensis* trichomes were further crushed for up to 25 s, resulting in an average size of 15.6 μm . This is a similar size range to *C. reinhardtii*, 10 μm on average, and can be easily ingested by daphnids. Therefore, we used this fragmented *A. platensis* for the following experiments.

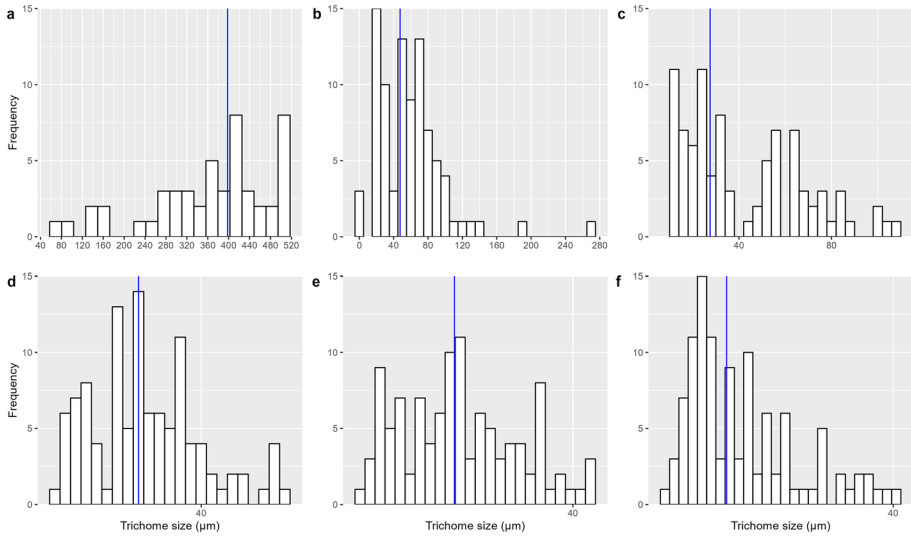


Fig. 1 Size distributions of *Arthrospira platensis* trichomes fragmented with a bead crusher at 0, 5, 10, 15, 20, and 25 s represented as a, b, c, d, e, and f, respectively. Blue vertical lines represent median values

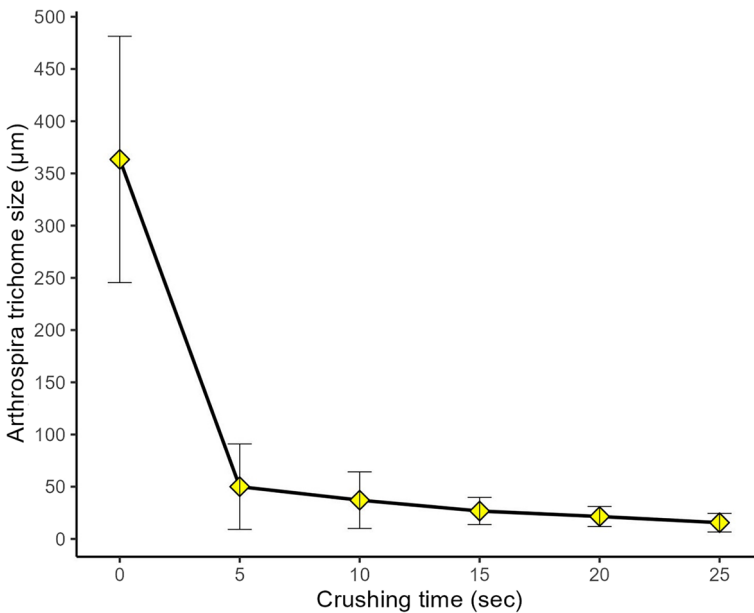


Fig. 2 Average trichome sizes of *Arthrospira platensis* at different times of crushing. Vertical bars represent standard deviation

Table 3 Phosphorus (P), carbon (C), and nitrogen (N) composition of *Arthrospira platensis* and *Chlamydomonas reinhardtii*

Microalgae	Contents (mg g dry-wt ⁻¹)			C:P	C:N
	P	C	N		
<i>A. platensis</i>	10.3 ± 0.6	477.3 ± 21.2	123.6 ± 5.2	46.3	3.9
<i>C. reinhardtii</i>	15.4 ± 0.8	546.3 ± 33.9	114.3 ± 6.5	35.5	4.8

Elemental composition of the two microalgae

The C, N, and P composition of *A. platensis* and *C. reinhardtii* cells is shown in Table 3. P contents in *A. platensis* and *C. reinhardtii* were 10.3 ± 0.6 and 15.4 ± 0.8 mg g dry weight⁻¹, respectively. The C:P ratios in *A. platensis* and *C. reinhardtii* were 46.3 and 35.5 dry weight, while C:N ratios were 3.9 and 4.8 dry weight, respectively. There were no noticeable differences in the composition of the elements between the two microalgae.

Survival and growth of *D. magna*

All experimental animals fed exclusively on *A. platensis*, and those without food (starvation) died within 5 days (Fig. 3). On the other hand, animals fed on *A. platensis* supplemented with at least 20% *C. reinhardtii* survived longer than 5 days. The survival rates increased with increasing supplementation of *C. reinhardtii*. Although more than 50% of daphnids fed on 80% *C. reinhardtii* alone died within 6 days old, the remaining animals produced eggs and neonates.

Growth rates of the daphnids increased from 0.25 ± 0.031 day⁻¹ to 0.37 ± 0.041 day⁻¹ with increasing proportions of *C. reinhardtii* in the mixtures from 20 to 80% (Fig. 4). The differences among the treatments were statistically significant (Table 4). The growth rate in the treatment of 80:20 of AP:CR was lower than that in 0:20, while that in 20:80 was higher than that in 0:80 (Fig. 4).

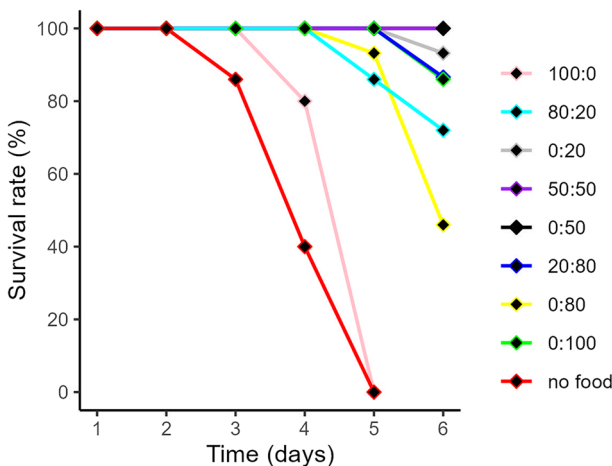


Fig. 3 Survival rates of *Daphnia magna* at different supply ratios of *Arthrospira platensis* to *Chlamydomonas reinhardtii* (AP:CR) as food during the study period

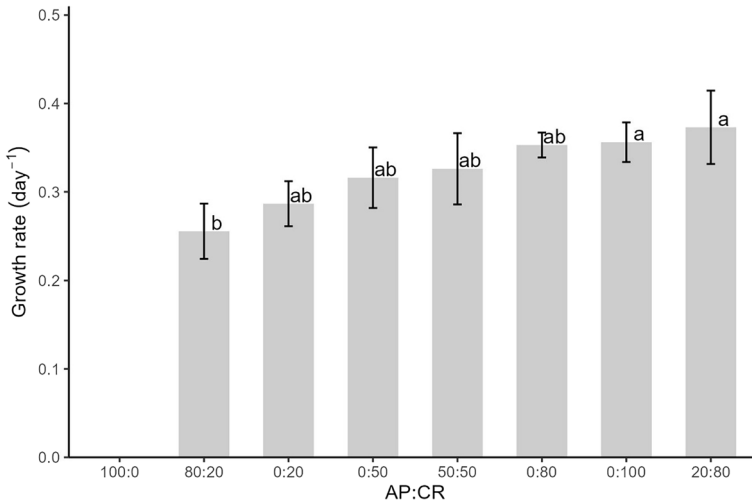


Fig. 4 Average specific growth rates of *Daphnia magna* reared with a mixture of *Arthrospira platensis* (AP) and *Chlamydomonas reinhardtii* (CR) at different ratios from 100:0, 80:20, 50:50, 20:80, and 0:100 of AP:CR, and exclusively on CR at 20%, 50%, and 80% of 4 mg C L⁻¹. Vertical bars denote standard deviation. Different letters above each column indicate significant differences by post hoc test using Tukey's HSD

Table 4 Results of one-way analysis of variance and post hoc Tukey's HSD test for the effects of food treatments on growth of *Daphnia magna*. *Df*, degrees of freedom; *SS*, sum of square; *MS*, mean square; *F*, *F* value; and *p*, *p* value

	<i>Df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>p</i>
Between groups	6	0.03048	0.005080	4.899	0.00793
Within group	13	0.01348	0.001037		

Bartlett's K-squared = 1.6583, *df* = 6, *p* = 0.9483

Discussion

Poor manageability of some cyanobacteria owing to their long chain, spiral, or colonial forms is one of the major barriers in ingestion and trophic transfer of energy and C to zooplankton (Bednarska et al. 2014). Mechanical interference with the filtering process is one reason for the inferior assimilation of cyanobacterial C to zooplankton (Porter and McDonough 1984). Although the trichome size of *A. platensis* (ca. 363 μm on average) was too large for daphnids, ingestion was easy when the size was reduced to <20 μm after fragmentation. We found, however, that daphnids could not survive when fed on such fragmented *A. platensis* alone. This implies that *A. platensis* lacks some essential nutrients mandatory to the survival and growth of daphnids.

Supplementation of *A. platensis* by just 20% of *C. reinhardtii* to total amount of food enhanced the survival and growth rates of daphnids, but these rates were lower than daphnids exclusively fed on *C. reinhardtii* at 20% supply. This suggests that the shortage of some essential elements in *A. platensis* for daphnid growth cannot be improved by a small supplementation of *C. reinhardtii*. Growth improved when the daphnids were fed on >50% supplementation of *C. reinhardtii*. In 80% supplementation of *C.*

reinhardtii, the growth rate was higher than those daphnids fed on *C. reinhardtii* alone. This suggests that daphnids may be able to digest *A. platensis* and that it can contribute more effectively to growth once the essential nutrients are compensated by addition of a suitable alga such as *C. reinhardtii*. Similar studies have also indicated that daphnids in cyanobacterial food needs at least 50% eukaryotic microalgae to meet the nutritional limitations of cyanobacteria (Martin-Creuzburg et al. 2008; Pietrzak et al. 2010; Wenzel et al. 2012). The use of cyanobacteria mixed with other better-quality microalgae has been found to enhance daphnid growth (Gulati and Demott 1997; Urabe and Waki 2009; Bednarska et al. 2014). This clearly explains that, even though cyanobacteria alone cannot sustain zooplankton life history traits, they can contribute to better growth and reproduction once their limitations are relaxed.

The poor nutritional quality of food algae for rearing daphnids is probably related to the limitation of essential nutrients. The trophic transfer of C and energy is limited by a small subset of elements and their proportions in the diet (Demott et al. 1991; Gulati and Demott 1997). Models of nutrient recycling and energy flow in zooplankton have revealed that the C:P ratio of zooplankton species is relatively more constant than that of their phytoplankton food. Stoichiometric variation in the algal food, mainly the low availability of P, affects zooplankton by direct elemental limitations, reducing digestibility and declining PUFA content in the diet (Müller-Navarra 1995; Urabe et al. 1997; Gulati and Demott 1997). In this study, the composition of elements in *A. platensis* appeared similar to that of *C. reinhardtii*, suggesting the availability of sufficient C, N, and P to rear daphnids. The C:P dry weight ratios of *A. platensis* (46.3) were well below the threshold of 116 for daphnid growth (Urabe et al. 1997, 2018). This demonstrates that elemental limitation is an unlikely explanation for the poor quality of *A. platensis* to rear daphnids.

Another reason for the poor quality of *A. platensis* for supporting daphnid growth might be the absence or insufficient availability of dietary lipids, especially PUFA and sterols. Previous studies have shown that 74% of lipid content of *C. reinhardtii* is unsaturated fatty acids (USFA) of which 48% are omega-3 fatty acids, while in *Spirulina* (in commercial *Arthrospira* powder), 38.6% of the lipid content was USFA with < 1.5% omega-3 fatty acid. In addition, alpha-linolenic acid, an important PUFA for daphnid growth, was found to be 42.4% in *C. reinhardtii* and 0.12% in *Spirulina* (Darwish et al. 2020). The most biologically important PUFAs for daphnid growth and reproduction such as alpha-linolenic acid, arachidonic acid, eicosapentaenoic acid, and docosahexaenoic acid are found in smaller quantities in *Spirulina platensis* (= *A. platensis*) (Tokuşoglu and Ünal 2003). This implies that insufficient availability of biologically important PUFAs in *Arthrospira* may contribute to its inferior performance in supporting daphnid growth.

Previous studies have clearly demonstrated that the poor quality of cyanobacteria for zooplankton is due to lack of sterols, which are important lipids responsible for cell membrane fluidity and are precursors of steroid hormones (Elert et al. 2003; Martin-Creuzburg and Elert 2004; Martin-Creuzburg et al. 2005, 2008, 2009). Crustaceans convert phytosterols to cholesterol (Teshima 1971). It has been shown that sterols are primarily limiting elements for daphnid growth and play an important role in juvenile development (Martin-Creuzburg et al. 2011). Daphnid growth was initially limited by sterol availability but switched to PUFA once sterols shortages are compensated (von Elert 2002; Martin-Creuzburg et al. 2005, 2008). The premature death of daphnids when they fed on *A. platensis* in this study might be associated with lack of sterols.

Conclusions

Although *A. platensis* was ingestible by *D. magna* after appropriate fragmentation, it does not support survival and somatic growth of daphnids. *A. platensis* supplemented with *C. reinhardtii* as a standard algal food enhanced the survival and growth of the daphnids, suggesting the limitation of essential nutrients in *A. platensis* to support daphnid's life history traits. Although such insufficiency might be the cause of the poor nutritional quality of *A. platensis* for rearing *D. magna*, a small addition of *A. platensis* to standard microalgal foods would contribute to better daphnid growth than when standard foods are fed exclusively.

Acknowledgements We express our gratitude to Dr. Shoko Hosoi-Tanabe for her assistance in using the bead crusher for fragmenting *A. platensis* trichomes.

Author contribution All authors contributed to the study idea and experimental design. Conducting the experiment, data analysis, and first draft manuscript preparation were performed by A.M. and revised by S.B., X.L., and M.M. All authors commented on the manuscript and read and approved the final manuscript.

Funding This study was supported by the Science and Technology Research Partnership for Sustainable Development (grant number JPMJSA2005) funded by Japan Science and Technology Agency/Japan International Cooperation Agency; Grants-in-Aid for Scientific Research (22H02425) from the Japan Society for the Promotion of Science to SB; and Grants-in-Aid for Scientific Research (20K15586) from the Japan Society for the Promotion of Science to XL.

Data availability All data generated or analyzed during this study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

References

- Altmann BA, Rosenau S (2022) *Spirulina* as animal feed: opportunities and challenges. Foods 11. <https://doi.org/10.3390/foods11070965>
- Bednarska A, Pietrzak B, Pijanowska J (2014) Effect of poor manageability and low nutritional value of cyanobacteria on *Daphnia magna* life history performance. J Plankton Res 36:838–847. <https://doi.org/10.1093/plankt/fbu009>
- Bukovinszky T, Verschoor AM, Helmsing NR et al (2012) The good, the bad and the plenty: interactive effects of food quality and quantity on the growth of different *Daphnia* species. PLoS ONE 7:e42966. <https://doi.org/10.1371/journal.pone.0042966>
- Damtie YA, Berlie AB, Gessese GM (2022) Impact of water hyacinth on rural livelihoods: the case of Lake Tana, Amhara region, Ethiopia Heliyon 8:e09132. <https://doi.org/10.1016/j.heliyon.2022.e09132>
- Damtie YA, Berlie AB, Gessese GM, Ayalew TK (2022) Characterization of water hyacinth (*Eichhornia crassipes* Mart.Solms) biomass in Lake Tana, Ethiopia. All Life 15:1126–1140. <https://doi.org/10.1080/26895293.2022.2134933>
- Darwish R, Gedi MA, Akepach P et al (2020) *Chlamydomonas reinhardtii* is a potential food supplement with the capacity to outperform *Chlorella* and *Spirulina*. Appl Sci (Switzerland) 10:1–17. <https://doi.org/10.3390/app10196736>
- Demott WR, Wayne F, Zhang Q-X, Carmichael WW (1991) Effects of toxic cyanobacteria and purified toxins on the survival and feeding of a copepod and three species of *Daphnia* Limnol Oceanogr 36:1346–1357

- Dersseh K et al (2019) Potential of water hyacinth infestation on Lake Tana, Ethiopia: a prediction using a GIS-based multi-criteria technique. *Water* (Basel) 11:1921. <https://doi.org/10.3390/w11091921>
- Dunn K, Maart B, Rose P (2013) *Arthrospira* (*Spirulina*) in tannery wastewaters. Part 2: evaluation of tannery wastewater as production media for the mass culture of *Arthrospira* biomass. *Water SA* 39:279–284. <https://doi.org/10.4314/wsa.v39i2.12>
- Elert EV, Martin-Creuzburg D, Le Coz JR (2003) Absence of sterols constrains carbon transfer between cyanobacteria and a freshwater herbivore (*Daphnia galeata*). *Proc R Soc Lond B Biol Sci* 270:1209–1214. <https://doi.org/10.1098/rspb.2003.2357>
- Elsler JJ, Acharya K, Kyle M et al (2003) Growth rate-stoichiometry couplings in diverse biota. *Ecol Lett* 6:936–943. <https://doi.org/10.1046/j.1461-0248.2003.00518.x>
- Fink P, Pfiltisch C, Marin K (2011) Dietary essential amino acids affect the reproduction of the keystone herbivore *Daphnia pulex* PLoS ONE 6:e28498. <https://doi.org/10.1371/journal.pone.0028498>
- Freese HM, Martin-Creuzburg D (2013) Food quality of mixed bacteria–algae diets for *Daphnia magna* *Hydrobiologia* 715:63–76. <https://doi.org/10.1007/s10750-012-1375-7>
- Geller W, Müller H (1981) The filtration apparatus of Cladocera: filter mesh-sizes and their implications on food selectivity. *Oecologia* 49:316–321. <https://doi.org/10.1007/BF00347591>
- Gentscheva G, Nikolova K, Panayotova V et al (2023) Application of *Arthrospira platensis* for medicinal purposes and the food industry: a review of the literature. *Life* 13:845. <https://doi.org/10.3390/life13030845>
- Gulati R, Demott W (1997) The role of food quality for zooplankton: remarks on the state-of-the-art, perspectives and priorities. *Freshw Biol* 38:753–768. <https://doi.org/10.1046/j.1365-2427.1997.00275.x>
- Hartnett R (2019) Variation in life-history traits among *Daphnia* and its relationship to species-level responses to phosphorus limitation. *R Soc Open Sci* 6:191024. <https://doi.org/10.1098/rsos.191024>
- Hultberg M, Lind O, Birgersson G, Asp H (2017) Use of the effluent from biogas production for cultivation of *Spirulina* *Bioprocess Biosyst Eng* 40:625–631. <https://doi.org/10.1007/s00449-016-1726-2>
- Ichimura T (1971) Sexual cell division and conjugation-papilla formation in sexual reproduction of *Closterium strigosum*. In: proceedings of the seventh international seaweed symposium, University of Tokyo Press, Tokyo, 208–214
- Kimura S, Yamada T, Ban S et al (2019) Nutrient removal from anaerobic digestion effluents of aquatic macrophytes with the green alga, *Chlorella sorokiniana* *Biochem Eng J* 142:170–177. <https://doi.org/10.1016/j.bej.2018.12.001>
- Martin-Creuzburg D, Elert E, Von (2004) Impact of 10 dietary sterols on growth and reproduction of *Daphnia galeata* *J Chem Ecol* 30:483–500. <https://doi.org/10.1023/B:JOEC.0000018624.94689.95>
- Martin-Creuzburg D, Wacker A, Von Elert E (2005) Life history consequences of sterol availability in the aquatic keystone species *Daphnia* *Oecologia* 144:362–372. <https://doi.org/10.1007/s00442-005-0090-8>
- Martin-Creuzburg D, Von Elert E, Hoffmann KH (2008) Nutritional constraints at the cyanobacteria–*Daphnia magna* interface: the role of sterols. *Limnol Oceanogr* 53:456–468. <https://doi.org/10.4319/lo.2008.53.2.0456>
- Martin-Creuzburg D, Sperfeld E, Wacker A (2009) Colimitation of a freshwater herbivore by sterols and polyunsaturated fatty acids. *Proc R Soc Biol Sci* 276:1805–1814. <https://doi.org/10.1098/rspb.2008.1540>
- Martin-Creuzburg D, Beck B, Freese HM (2011) Food quality of heterotrophic bacteria for *Daphnia magna*: evidence for a limitation by sterols. *FEMS Microbiol Ecol* 76:592–601. <https://doi.org/10.1111/j.1574-6941.2011.01076.x>
- Martins CF, Ribeiro DM, Costa M et al (2021) Using microalgae as a sustainable feed resource to enhance quality and nutritional value of pork and poultry meat. *Foods* 10:2933. <https://doi.org/10.3390/foods10122933>
- Matos ÂP, Vadelvelo A, Bahri PA, Moheimani NR (2021) Anaerobic digestate abattoir effluent (ADAE), a suitable source of nutrients for *Arthrospira platensis* cultivation. *Algal Res* 54:102216. <https://doi.org/10.1016/j.algal.2021.102216>
- Müller-Navarra DC (1995) Biochemical versus mineral limitation in *Daphnia* *Limnol Oceanogr* 40:1209–1214. <https://doi.org/10.4319/lo.1995.40.7.1209>
- Murphy J, Riley JP (1962) A modified single solution method for the determination of phosphate in natural waters. *Anal Chim Acta* 27:31–36. [https://doi.org/10.1016/S0003-2670\(00\)88444-5](https://doi.org/10.1016/S0003-2670(00)88444-5)
- Nuhu AA (2013) *Spirulina* (*Arthrospira*): an important source of nutritional and medicinal compounds. *J Mar Biol* 2013:1–8. <https://doi.org/10.1155/2013/325636>
- O’Sullivan C, Rounsefell B, Grinham A et al (2010) Anaerobic digestion of harvested aquatic weeds: water hyacinth (*Eichhornia crassipes*), cabomba (*Cabomba Caroliniana*) and salvinia (*Salvinia molesta*). *Ecol Eng* 36:1459–1468. <https://doi.org/10.1016/j.ecoleng.2010.06.027>

- Ogawa T, Terui G (1970) Studies on the growth of *Spirulina platensis*, (I) on the pure culture of *Spirulina platensis* J Ferment Technol 48:361–367
- Pietrzak B, Grzesiuk M, Bednarska A (2010) Food quantity shapes life history and survival strategies in *Daphnia magna* (Cladocera). Hydrobiologia 643:51–54. <https://doi.org/10.1007/s10750-010-0135-9>
- Porter KG, McDonough R (1984) The energetic cost of response to blue-green algal filaments by cladocerans. Limnol Oceanogr 29:365–369. <https://doi.org/10.4319/lo.1984.29.2.0365>
- R Core Team (2022) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. Accessed at: <https://www.R-project.org/>. Accessed 10 Feb 2023
- Spínola MP, Costa MM, Prates JAM (2022) Digestive constraints of *Arthrospira platensis* in poultry and swine feeding. Foods 11:2984. <https://doi.org/10.3390/foods11192984>
- Teshima S-I (1971) Bioconversion of β -sitosterol and 24-methylcholesterol to cholesterol in marine crustacea. Comp Biochem Physiol Part B: Comp Biochem 39:815–822. [https://doi.org/10.1016/0305-0491\(71\)90105-2](https://doi.org/10.1016/0305-0491(71)90105-2)
- Thomas PK, Kunze C, Van de Waal DB et al (2022) Elemental and biochemical nutrient limitation of zooplankton: a meta-analysis. Ecol Lett. <https://doi.org/10.1111/ele.14125>
- Tokuşoglu Ö, Ünal MK (2003) Biomass nutrient profiles of three microalgae: *Spirulina platensis*, *Chlorella vulgaris*, and *Isochrysis galbana*. J Food Sci 68:1144–1148. <https://doi.org/10.1111/j.1365-2621.2003.tb09615.x>
- Urabe J, Shimizu K, Kawabata K, Nakanishi M (1996) Grazing and food size selection of zooplankton community in Lake Biwa during BITEK '93. Japanese J Limnol (Rikusuigaku Zasshi) 57:27–37. <https://doi.org/10.3739/rikusui.57.27>
- Urabe J, Clasen J, Sterner RW (1997) Phosphorus limitation of *Daphnia* growth: is it real? Limnol Oceanogr 42:1436–1443. <https://doi.org/10.4319/lo.1997.42.6.1436>
- Urabe J, Waki N (2009) Mitigation of adverse effects of rising CO₂ on a planktonic herbivore by mixed algal diets. Glob Chang Biol 15:523–531. <https://doi.org/10.1111/j.1365-2486.2008.01720.x>
- Urabe J, Shimizu Y, Yamaguchi T (2018) Understanding the stoichiometric limitation of herbivore growth: the importance of feeding and assimilation flexibilities. Ecol Lett 21:197–206. <https://doi.org/10.1111/ele.12882>
- Villamagna AM, Murphy BR (2010) Ecological and socio-economic impacts of invasive water hyacinth (*Eichhornia crassipes*): a review. Freshw Biol 55:282–298. <https://doi.org/10.1111/j.1365-2427.2009.02294.x>
- von Elert E (2002) Determination of limiting polyunsaturated fatty acids in *Daphnia galeata* using a new method to enrich food algae with single fatty acids. Limnol Oceanogr 47:1764–1773. <https://doi.org/10.4319/lo.2002.47.6.1764>
- Wacker A, Martin-Creuzburg D (2012) Biochemical nutrient requirements of the rotifer *Brachionus calyciflorus*: co-limitation by sterols and amino acids. Funct Ecol 26:1135–1143. <https://doi.org/10.1111/j.1365-2435.2012.02047.x>
- Wan D, Wu Q, Kuča K (2021) *Spirulina*. In: Nutraceuticals: Efficacy, safety and toxicity, 2nd edn. Elsevier, Amsterdam, pp 959–974
- Wang Y, Tibbetts S, McGinn P (2021) Microalgae as sources of high-quality protein for human food and protein supplements. Foods 10:3002. <https://doi.org/10.3390/foods10123002>
- Wenzel A, Bergström AK, Jansson M, Vrede T (2012) Survival, growth and reproduction of *Daphnia galeata* feeding on single and mixed *Pseudomonas* and *Rhodomonas* diets. Freshw Biol 57:835–846. <https://doi.org/10.1111/j.1365-2427.2012.02751.x>
- Wenzel A, Vrede T, Jansson M, Bergström AK (2021) *Daphnia* performance on diets containing different combinations of high-quality algae, heterotrophic bacteria, and allochthonous particulate organic matter. Freshw Biol 66:157–168. <https://doi.org/10.1111/fwb.13626>
- Williams AE (2004) Water hyacinth—the world's most problematic weed. Water Encyclopedia 479–484. <https://doi.org/10.1002/047147844X.sw1116>

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