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Analysis of formulae for determination of seaweed growth rate

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Abstract The increasing demand for products derived from seaweeds has led to an increasing amount of research being directed towards studies related to their growth and productivity. Several investigators have attempted to develop different formulae for the estimation of growth rates and caused confusion to the readers. In this study, accuracy and reliability of the average growth rate formulae were analyzed using geometric progression theory and compared to each other. The lowest degree of error (0.023 %) and the highest matched point (61.90 %) was achieved by applying $[(W_t/W_0)^{1/t}-1]\times 100$ % in growth rate determination. This formula has been tested and proven to be the most accurate among all the currently available ones.

Keywords Growth rate · Seaweed · Formulae · Calculation · Geometric progression

Introduction

The accelerated development of the commercial seaweed industry has resulted in an expansion in the scope of research related to the improvement of seaweed yield and quality (Dawes and Koch 1991; McHugh 2003; Reddy et al. 2008; Baweja et al. 2009; Góes and Reis 2012). Referring to cultivation studies, which cover ecology, farming, and micropropagation, there are several sets of formulae used in growth rate calculation and determination, especially for the commercially important *Kappaphycus alvarezii*, *Kappaphycus striatum*, and *Eucheuma denticulatum* (Glenn and Doty 1992; Mtolera et al. 1995; Luhan and Sollesta 2010; Loureiro et al. 2010; Schmidt et al. 2010). Although the formula names are almost the same, the calculation theory, units, and the formulae are not connected well (Table 1).

However, there is still a similarity between the formulae applied by different authors, which is the growth rate unit (% day^{-1}). With reference to this common unit, the seaweed is said to grow in a constant or average percentage of increment in weight or size over a time period which follows the theory of geometric progression. A geometric progression is a sequence of numbers where each term after the first is found by multiplying the previous one by a fixed nonzero number called the common ratio. Thus, the growth of seaweed can be said as an example of geometric progression, where the weight or size of seaweed increases with a common multiplier or ratio.

Generally, growth rate is defined as the speed of growth over time. For example, 2 g day^{-1} means growth of 2 g every day, or 5 % day^{-1} can be defined as 5 % increase of weight or diameter every day. However, confusion always occurs as there is no standardization of formula calculation. Readers often are confounded by published data as different formulae are applied by different researchers. Although the units were the same in most of the calculations, the results are not comparable as different formulae are applied. Thus, these formulae were evaluated and compared here for their accuracy and reliability.

Materials and methods

An accuracy test was carried out by determining the degree of error of the growth rate formulae, as reported in Table 1. In order to perform this test, a seaweed sample was projected to

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Table 1 Currently existing calculation formulae for growth rate and relative and specific growth rate

Formula name	Formula	Unit	Reference
Daily growth rate	$\left(\frac{\ln\frac{W_t}{W_0}}{t}\right) \times 100\,\%$	% day^{-1}	Loureiro et al. 2010, 2012; Borlongan et al. 2011; Góes and Reis 2012
Daily growth rate/growth rate	$\left[\left(\frac{W_t}{W_0}\right)^{\frac{1}{t}} - 1\right] \times 100\,\%$	% day^{-1}	Mtolera et al. 1995; Gerung and Ohno 1997; Aguirre-von-Wobeser et al. 2001; Bulboa et al. 2007; Hayashi et al. 2007a, b, 2011; Hung et al. 2009
Growth rate	$\left[\left(\frac{W_t}{W_0}\right) - 1\right] \times \frac{100}{t}\%$	% day^{-1}	Schmidt et al. 2010
Relative growth rate	$\frac{\ln W_t - \ln W_0}{t}$	g g^{-1} day^{-1}	Glenn and Doty 1992
Specific growth rate	$\frac{\ln W_t - \ln W_0}{t} \times 100\,\%$	% day^{-1}	Luhan and Sollesta 2010

Although the formula names are slightly different compared to each other, the objective of the formula basically is to refer to growth rate. With reference to the formula column, W_0 is the initial wet weight, W_t is the final wet weight, and t is days of culture

have an initial weight of 20 g and grew to 30 g after a week of cultivation. With the given initial and final weights, growth rates using different formulae were calculated (as shown in Table 2). Then, by using the calculated growth rate associated with the given initial weight (20 g), recalculation was carried out using geometric progression theory, and the respective final weight which differed among the formulae was obtained. After that, the degree of error was calculated to determine the accuracy of each of the formulae tested.

Three propagules of micropropagated *K. alvarezii* were cultured in an outdoor nursery with filtered seawater and continuous aeration for 2 weeks. In order to exclude inconsistent growth data due to adaptation at the beginning of cultures, a set of daily weight data was obtained in the second week (namely day 1 to day 7) and used to compare all the tested formulae regarding their reliability in determining growth rate. The experimental mass which reflected the projected growth rate was defined as "matched weight". With the determined growth rate from each formula, the respective weights from day 1 to day 7, with reference to day 0 as initial weight, were computed. Then, the number of matched weight was highlighted and used for match point determination, where the percentages of matched data were determined.

Results

With reference to Table 2, the formula $[(W_t/W_0)^{1/t} - 1] \times 100$ % showed the lowest degree of error (0.023 %) as compared to the rest (range from 1.140 to 8.037 %). Thus, by using this formula for growth rate determination, the result is reproducible. In order to check the reliability of each formula, a set of weight data from the cultivation of *Kappaphycus* under optimized growth condition (Table 3)

Table 2 Comparison between formulae was carried out with a given initial weight (W_0) of 20 g and final weight (W_t) of 30 g and was recorded after t=7 days of cultivation

	Calculations			
Formula	$\left(\frac{ln\frac{W_t}{W_0}}{t}\right) \times 100\,\%$	$\left[\left(\frac{W_t}{W_0}\right)^{\frac{1}{t}} - 1\right] \times 100\,\%$	$\left[\left(\frac{W_t}{W_0}\right) - 1\right] \times \frac{100}{t}\%$	$\frac{\ln W_t - \ln W_0}{t} \times 100\,\%$
Growth rate	$\left(\frac{ln\frac{30}{20}}{7}\right) \times 100\,\%$ =5.79 % day^{-1}	$\left[\left(\frac{30}{20}\right)^{\frac{1}{7}} - 1\right] \times 100\,\%$ =5.96 % day^{-1}	$\left[\left(\frac{30}{20}\right) - 1\right] \times \frac{100}{7}\%$ =7.14 % day^{-1}	$\frac{\ln 30 - \ln 20}{7} \times 100\,\%$ =5.79 % day^{-1}
Using the calculated growth rate, the final weight was predicted with the given initial weight using geometric progression theory.	Final weight$_{predict}$ $= W_0 \times \left(\frac{GR}{100} + 1\right)^t$ $= 20 \times \left(\frac{5.79}{100} + 1\right)^7$ =29.658 g	Final weight$_{predict}$ $= W_0 \times \left(\frac{GR}{100} + 1\right)^t$ $= 20 \times \left(\frac{5.96}{100} + 1\right)^7$ =29.993 g	Final weight$_{predict}$ $= W_0 \times \left(\frac{GR}{100} + 1\right)^t$ $= 20 \times \left(\frac{7.14}{100} + 1\right)^7$ =32.411 g	Final weight$_{predict}$ $= W_0 \times \left(\frac{GR}{100} + 1\right)^t$ $= 20 \times \left(\frac{5.79}{100} + 1\right)^7$ =29.658 g
Degree of error	$\frac{\lvert W_{predict} - W_t \rvert}{W_t} \times 100\,\%$ $= \frac{\lvert 29.658 - 30 \rvert}{30} \times 100\,\%$ =1.14 %	$\frac{\lvert W_{predict} - W_t \rvert}{W_t} \times 100\,\%$ $= \frac{\lvert 29.993 - 30 \rvert}{30} \times 100\,\%$ =0.023 %	$\frac{\lvert W_{predict} - W_t \rvert}{W_t} \times 100\,\%$ $= \frac{\lvert 32.411 - 30 \rvert}{30} \times 100\,\%$ =8.037 %	$\frac{\lvert W_{predict} - W_t \rvert}{W_t} \times 100\,\%$ $= \frac{\lvert 29.658 - 30 \rvert}{30} \times 100\,\%$ =1.14 %

Table 3 Set of experimental data of seaweed (*Kappaphycus*) weight (g) from day 0 to day 7 under the same treatment of cultivation

Replicates	Day							
	0	1	2	3	4	5	6	7
R1	26	27	29	31	32	34	36	38
R2	23	26	27	28	29	30	33	37
R3	18	20	21	23	23	25	26	28

was used for comparison. Among all the tested formulae, $[(W_t/W_0)^{1/t}-1]\times 100$ % showed the highest matched percentage, which is 61.90 %, whereas the lowest was achieved by using the formula $[(W_t/W_0)-1]\times 100$ %/t (19.05 %), as reported in Table 4.

Discussion

Although all the formulae state the application of logarithm (log or ln) or index to relate with the life growth pattern, all calculations actually refer to the average growth rate in the stated period, as shown by their common units (%day^{-1}). Thus, geometric progression theory was applied to predict the Final weight$_{\text{predict}}$ using their respective growth rate results for accuracy or degree of error determination. Geometric progression is a series of data sharing a constant multiplication ratio (Ivanova 1989). In this study, seaweed growth was defined as the percentage of growth in each day, where the growth rate was actually the multiplication ratio stated in geometric progression theory.

The sigmoid pattern of growth was nullified, while the geometric progression was applied in the formula $[(W_t/W_0)^{1/t}-1]\times 100$ % as a short time period (2–7 days) was calculated. Seaweeds are very sensitive to their environment, and their growth is always a responding variable. Thus, for an extended period of calculation (more than 7 days), other than considering real-life growth pattern, many uncontrolled variables need to be taken into consideration. However, the sigmoid growth pattern still can be observed by plotting growth rate over time, where the growth rate will plateau as the seaweed biomass increases.

Although the degree of error of the formula $[(W_t/W_0)^{1/t}-1]\times 100$ % is low, the matched percentage is considered low as well (61.90 %). The main reason is that the growth rate formula adopted the assumption of ideal constant conditions, where the growth of the seaweed is assumed to follow a steady increase of growth with a constant ratio. Seaweeds never grow ideally, and their environment is never constant. Also, uncontrolled factors such as weather and light intensity influence their growth rates. However, the formula $[(W_t/W_0)^{1/t}-1]\times 100$ % still achieved the highest matched percentage among the tested formulae, which make it the most reliable formula to be used in growth rate determination.

Growth rate determination is a basic measurement to determine the growth performance and response of a target culture. However, seaweed product yield is more significant than daily growth rate and plays an important role in production efficiencies (Lapointe and Ryther 1978). Studies done by Hayashi et al. (2011) and Reis et al. (2011) also indicated that carrageenan yields were significantly higher in salinity of about 25 ppt, although the determined daily growth rates are similar to those in higher saline media.

Table 4 By using the data set in Table 2 for comparison, the average growth rate (% day^{-1}) of the seaweeds from each treatment was determined. Then, by applying the respective calculated growth rate with the initial weight in day 0, weights from day 1 to day 7 were recalculated and matched with the experimental data in Table 3. Matched weight is in italics, and the percentage of matched points was determined

Formula	Samples	Growth rate (% day^{-1})	Weights calculated according to growth rate from day 1 to day 7 (g)								Number of matched	Total matched	Percentage (%)
			0	1	2	3	4	5	6	7			
$\left(\frac{\ln\frac{W_t}{W_0}}{t}\right)\times 100\,\%$	R1	5.42	26	*27*	*29*	30	*32*	*34*	*36*	*38*	6	10/21	47.62
	R2	6.79	23	25	26	*28*	30	32	34	36	1		
	R3	6.31	18	19	20	22	*23*	24	*26*	*28*	3		
$\left[\left(\frac{W_t}{W_0}\right)^{\frac{1}{t}}-1\right]\times 100\,\%$	R1	5.57	26	*27*	*29*	*31*	*32*	*34*	*36*	*38*	7	13/21	61.90
	R2	7.03	23	25	26	*28*	30	32	35	*37*	2		
	R3	6.52	18	19	20	22	*23*	*25*	*26*	*28*	4		
$\left[\left(\frac{W_t}{W_0}\right)-1\right]\times\frac{100}{t}\,\%$	R1	6.59	26	28	30	*31*	34	36	38	41	1	4/21	19.05
	R2	8.70	23	25	*27*	30	32	35	38	41	1		
	R3	7.94	18	19	*21*	*23*	24	26	28	31	2		
$\frac{\ln W_t-\ln W_0}{t}\times 100\,\%$	R1	5.42	26	*27*	*29*	30	*32*	*34*	*36*	*38*	6	10/21	47.62
	R2	6.79	23	25	26	*28*	30	32	34	36	1		
	R3	6.31	18	19	20	22	*23*	24	*26*	*28*	3		

Generally, factors that affect the growth rates may affect the specific seaweed product yield profile.

In conclusion, seaweeds exhibit a characteristic growth pattern which is marked by a rapid initial phase followed by decreased growth during later stages. This is due to self-shading as the inner parts of tissue are often shaded from exposure to light, which then reduces the photosynthesis rate. Thus, in order to determine growth rate more accurately, the time interval between data is recommended to be as short as weekly. However, daily data for calculation should be carefully considered as precision will be lost due to high sensitivity of seaweed growth to their environment. Overall, $[(W_t/W_0)^{1/t}-1]\times 100$ % should be used as the standard formulation for seaweed growth rate determination.

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