Comparative analysis of the relationship among age, weight, and energy requirement of common bottlenose dolphin (Tursiops truncatus)

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Abstract. The common bottlenose dolphin (*Tursiops truncatus*) is a well-known cetacean species, often seen in documentaries and captivity, such as zoos and aquariums. This study explores the relationships among age, weight, and energy requirements of captive dolphins to discover better dietary plans and care practices. Using data from three longitudinal studies conducted in the early 2000s, this research analyzed dolphins' body measurements and energy requirements. The findings reveal a positive correlation between the age and weight of bottlenose dolphins, suggesting that as dolphins age, their weight tends to increase. Conversely, a negative correlation between age and energy requirements, as well as weight and energy requirements, indicates that older and heavier dolphins require less energy per kilogram of body weight. These trends align with the results of the previous study; however, due to lactating females exhibiting significantly higher energy needs, the overall correlation levels were affected. These results underscore the importance of tailored feeding protocols based on dolphins' age and weight. To improve future studies, it is recommended to use standardized methodologies for measurement and sample selection and to expand the range of data sources. These results highlight the necessity of customized feeding protocols based on the age and weight of dolphins. To optimize the accuracy and representativeness of future analyses, it is recommended that methodologies for measurement and sample selection be standardized, and the range of data sources be broadened. This holistic approach will ultimately facilitate people's understanding of dolphin physiology and contribute to better conservation and welfare practices.

Keywords: Common bottlenose dolphin (Tursiops truncatus), captive dolphins, age, weight, energy requirements, dietary plans, care practices.

1. Introduction

The common bottlenose dolphin (*Tursiops truncatus*) is one of the most recognizable and arguably the best-known species among all cetaceans, frequently featured in documentaries and accessible for interaction in zoos and aquariums [1]. These agile creatures captivate people's attention with their beauty and intelligence. This research examines the relationships among age (in years), weight (in kg), and energy requirements (in Kcal/kg/day) of captive common bottlenose dolphins. An appropriate amount of energy intake and a balanced nutrient diet are essential for maintaining the health and wellness of the common bottlenose dolphin [2].

Common bottlenose dolphins experience several distinct developmental stages from birth to maturity, each characterized by unique energy requirements influenced by age, growth, and reproductive status. Initially, newborns rely on maternal care, transitioning to consuming solid food as calves [3]. As these young dolphins grow, understanding their dietary needs becomes increasingly crucial. During the juvenile stage, dolphins gain independence, refining hunting, and social skills, while adolescents approach adult size and sexual maturity [4]. They typically attain sexual maturity around ten years of age, with females reaching fertility between 5 to 10 years earlier than males, who mature between 8-13 years [5]. As adults, dolphins reach full size, with males typically larger than females, and engage in established social and reproductive behaviors [4]. This progression underscores the need to explore how these factors collectively impact energy consumption and overall health. Body size, particularly weight, plays a critical role in determining the energy requirements of common bottlenose dolphins. Various factors, including age, food consumption, and habitat, influence the weight of these dolphins, which typically ranges from 150 to 200 kg [6]. There are individual differences in the weight of common bottlenose dolphin; large bottlenose dolphins in the Pacific may reach 454 kg, and the maximum weight reported was an Eastern North Atlantic individual, who measured 650 kg [6]. This variation in weight among individuals highlights the complexity of accurately assessing and meeting their energy needs.

To maintain optimal health and well-being, the diet of common bottlenose dolphins must be carefully managed to reflect their diverse nutritional needs. Common bottlenose dolphins exhibit dietary diversity, preying on a variety of species like fish, squid, and crustaceans, with preferences often dictated by geographic location and local prey availability [7]. In their natural habitat, dolphins hunt their prey opportunistically. However, captive dolphins are reliant on the fish provided to them. The transition from natural hunting to captivity necessitates careful dietary planning. Trainers and veterinarians who are responsible for their care face the task of ensuring that the dolphins receive the optimal diet, comprising a variety and sufficient quantity of fish to fulfill all their nutritional requirements [2]. Overfeeding can lead to obesity and associated health issues while underfeeding or nutrient deficiencies can result in malnutrition and severe health problems.

As bottlenose dolphins are increasingly held in captivity for both conservation and research purposes, there has been a significant accumulation of data concerning their physical and behavioral characteristics [8, 9, 10, 11]. Most of this extensive data set has been meticulously recorded and thoroughly analyzed, providing valuable insights into various aspects of their physiology, behavior, and well-being. Despite this abundance of data, specific insights into how developmental stages affect energy requirements are scant [2]. This article aims to bridge this gap by conducting a comparative analysis of the energy requirements of common bottlenose dolphins in terms of their age and weight based on previous studies. By enhancing people's understanding of these relationships, this research can significantly improve conservation efforts, refine welfare practices, and deepen the comprehension of these remarkable marine mammals.

2. Method

2.1. Study Articles and Data Sources

This article analyzes three longitudinal studies that examine the age, food consumption, and body measurements of captive common bottlenose dolphins in three nations [2, 12, 13]. Kastelein *et al.*, 2002 report the body measurement and food consumption data of 19 Atlantic bottlenose dolphins housed at Harderwijk Marine Mammal Park in the Netherlands from 1965 to 1995. Kastelein *et al.*, 2005 report a similar set of data of 11 Atlantic bottlenose dolphins kept at Windsor Safari Park, UK, from 1979 to 1993/1994, and at Harderwijk Marine Mammal Park in the Netherlands from 1993/1994 to 1995. Reddy *et al.*, 1994 report the body measurement data and the energy requirement of 16 bottlenose dolphins housed in a netted enclosure in San Deigo Bay from 1989 to 1991. All three studies include subadult male and female dolphins, as well as pregnant and lactating female dolphins.

2.2. Sample Measurement and Data Collection

This article includes data samples of common bottlenose dolphins of various ages and both sexes. Eight data samples were collected from Kastelein *et al.*, 2002 (TtWs001, TtWs 005, TtWs006, TtWs007, TtWs008, TtWs002, TtWs003, TtWs010), five data samples were collected from Kastelein *et al.*, 2005 (TtZH006, TtZH010, TtZH007, TtWS005, TtWS007), and all the data sample were collected from Reddy *et al.*, 1994. Some data were listed in the table of the three studies, but more were extracted from graphs by extrapolating data points and comparing them with the axes. Existing data were recorded directly, while relevant raw data were processed and integrated to create the individual information table (Appendices, Table 1).

2.3. Data Processing and Data Analysis

All dolphins that have recorded age, body measurements, and food intake or energy requirements simultaneously from the three studies were collected to serve as the data sample for this research. Their serial number listed in previous studies were used again as their identity. For dolphins with recorded ages falling within a range, the median of that range is used as their official recorded age. If the median results in a decimal, it is rounded up to the nearest whole number. The weight of bottlenose dolphins in kg, defined as the average weight of an individual at a specific age, can be calculated from their body length using the equation body mass $= 17.261e^{0.0156(\text{body length} - 100)}$ [12]. The energy requirement in Kcal/kg/day for bottlenose dolphins is calculated by multiplying the daily food consumption weight by the caloric content of the consumed food, specifically the calories of the percentage of the fish or squid per kilo, and then dividing the result by the dolphin's average body weight, finalizing all data as Kcal/kg/day [12, 13, 14].

The R package [15] is used to analyze all data collected from the three kinds of literature, comparing the relationships among age (in years), average weight (in kg), and energy requirement (in Kcal/kg/day). A linear modeling method was employed to generate regression equations based on the data recorded in the individual information table. The coefficient determination (R^2) was computed from the regression plots to assess the strength of the correlation between the dependent variable on the y-axis and the independent variable on the x-axis.

3. Result

3.1. Geographic distribution and timeline of data collection caused a high variance of food resource

This research incorporates data derived from three significant longitudinal studies conducted over a broad geographic distribution and time span, highlighting diverse environments and dolphin populations. (Figure 1). The world map provided in Figure 1 illustrates the geographic distribution of the studies, with red circles indicating the specific locations where each study was conducted. This visual representation highlights the global nature of the research efforts and underscores the environmental variations that may influence the observed outcomes in dolphin physiology and behavior. Kastelein *et al.*, 2002 and 2005 conducted in Europe, these studies spanned from the late 1960s to the early 1990s. They provided comprehensive data on dolphin body measurements and dietary habits across several decades, offering a longitudinal perspective on the physiological and behavioral trends within captive dolphin populations. Reddy *et al.*, 1994 conducted this study in North America in the early 1990s, marked on the map in Figure 1. The geographic diversity of these studies is crucial for understanding regional variations in captive dolphin care and health, providing insights that are likely applicable across different dolphin populations worldwide.
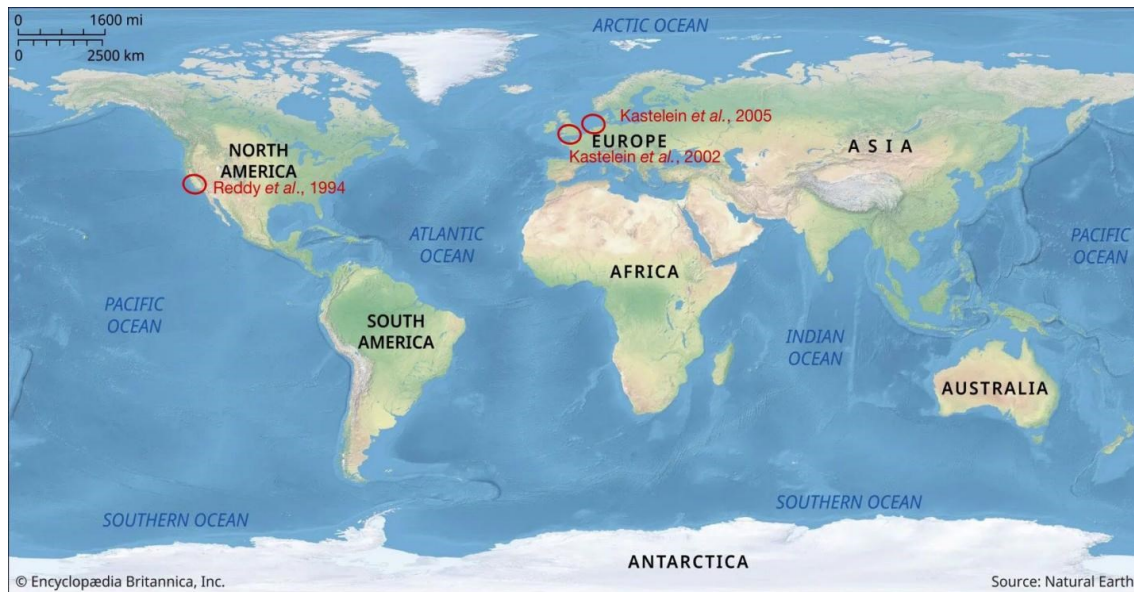
Figure 1. Geographic distribution of locations where selected research was performed on captive bottlenose dolphin

The analysis of daily food composition across different studies and periods reveals significant shifts in dietary management strategies for common bottlenose dolphins. These shifts are documented in Figures 2, 3, and 4, the total energy content of 1 kg of daily consumed food was calculated for periods before and after 1991, as reported by Kastelein *et al.*, 2002, with values of 1685 Kcal/day and 1768 Kcal/day, respectively. In Kastelein *et al.*, 2005, it was 1682 Kcal/day. These values were calculated separately and integrated into pie charts (Figure 5, Figure 6, Figure 7) to illustrate the differences in dietary composition over the years. Before 1991, the diet predominantly consisted of herring (65%) and mackerel (30%), with squid comprising only 5% of the total. Herring and mackerel, known for their high caloric value of 1580 Kcal/kg and 2050 Kcal/kg respectively, suggest a diet aimed at maximizing caloric intake, which could be indicative of a focus on growth or high-energy demands. The dietary composition after 1991 shows a reduced proportion of herring (60%) and an increase in mackerel (40%). By 1993, as illustrated in Figure 4, the diet diversified significantly, with the introduction of new fish types such as whiting and sprat, which account for 20% and 15% of the diet, respectively. The inclusion of sprat, particularly high in calories (2080 Kcal/kg), alongside the consistent presence of herring and mackerel, indicates an adaptive approach to dietary planning that possibly considers the varying nutritional needs of dolphins at different life stages or health conditions.
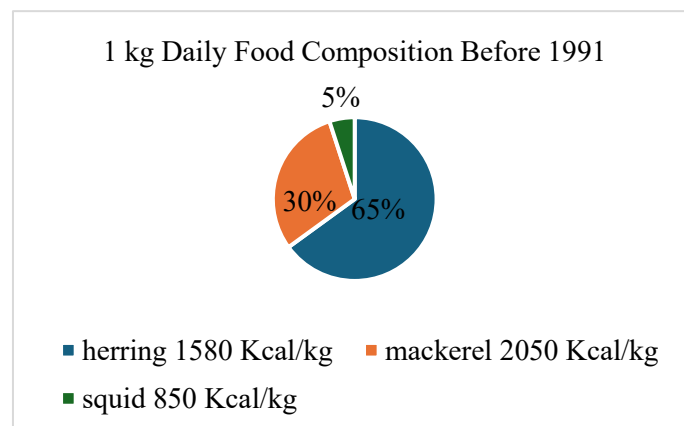

Figure 2. One kg daily food composition before 1991 from Kastelein *et al.*, 2002
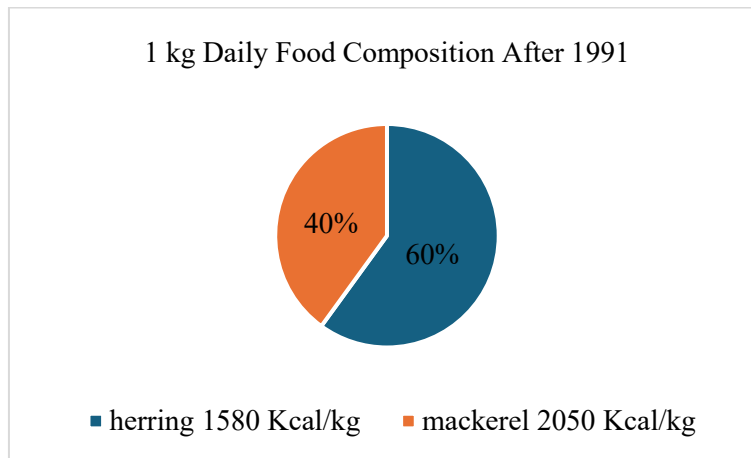
Figure 3. One kg daily food composition after 1991 from Kastelein *et al.*, 2002
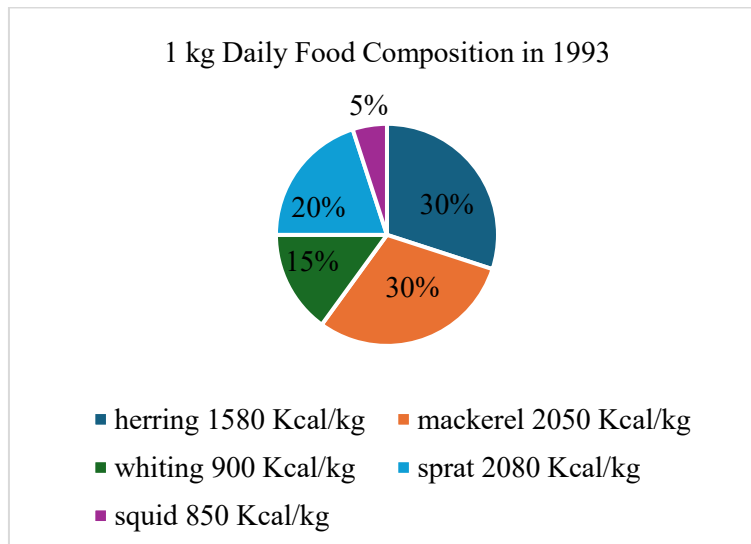

Figure 4. One kg daily food composition in 1993 from Reddy *et al.*, 1994

Across all figures, the data demonstrate a gradual evolution from a heavy herring and mackerel-based diet to a more diversified approach including lower-calorie fishlike squid and whiting. This transition in dietary components likely mirrors changes in dietary research, understanding of dolphin health needs, and possibly the influence of conservation practices on food sourcing.

3.2. Age positively influences body weight in common bottlenose dolphins

An individual information table (Table 1) was created based on processed data from 39 data samples of common bottlenose dolphins. This table lists the identity (serial number), age (in years), average weight (in kg), and energy requirement (in Kcal/kg/day) of the 39 data samples. Furthermore, to explore the relationships among the recorded data, three linear regression plots were generated to analyze: (1) the correlation between age (in years) and average weight (in kg) (Figure 5), (2) the correlation between age (in years) and energy requirement (in Kcal/kg/day) (Figure 6), and (3) the correlation between average weight (in kg) and energy requirement (in Kcal/kg/day) of bottlenose dolphins (Figure 7).
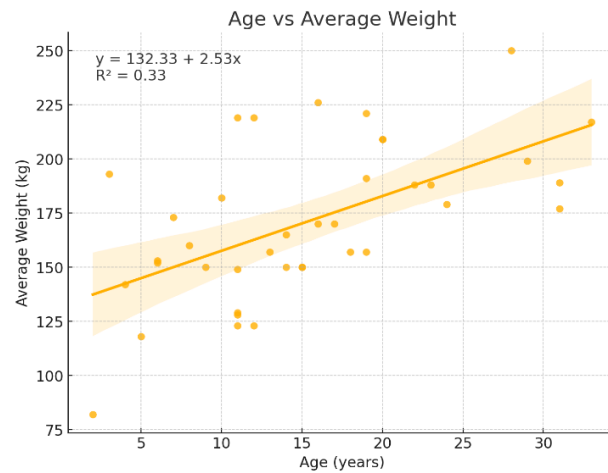
Figure 5. The relationship between age (in years) and average weight (in kg) of captive common bottlenose dolphin
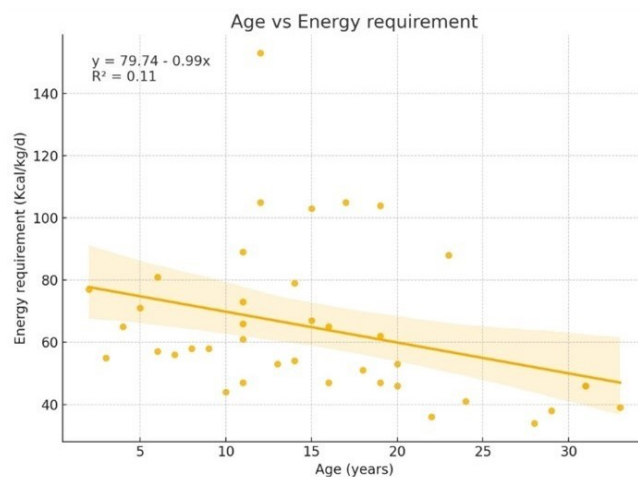

Figure 6. The relationship between age (in years) and energy requirement (in Kcal/kg/day) of captive common bottlenose dolphin
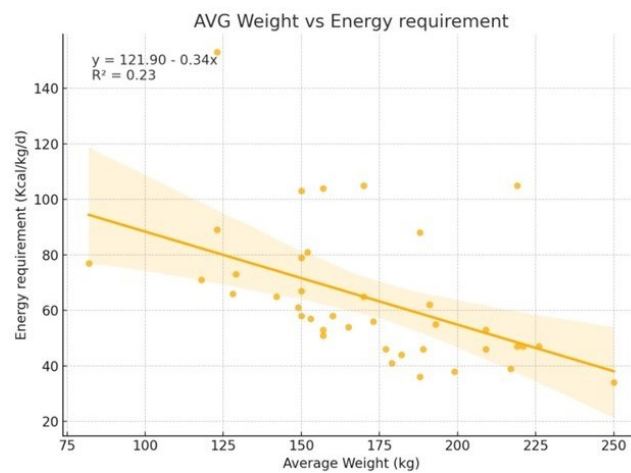

Figure 7. The relationship between average weight (in kg) and energy requirement (in Kcal/kg/day) of captive bottlenose dolphin

As shown in Figure 5, the age (in years) and average weight (in kg) of common bottlenose dolphins show a positive correlation with the regression equation y = 132.33 + 2.53x, indicating that older dolphins tend to have a larger body size. However, the data poorly fit the regression model (R^2 value is 0.33), this might be due to the limited size of samples and big variation among the collected samples. The scattered data points on the plot highlight significant individual differences in weight among dolphins of all ages. For instance, the heaviest dolphin weighs 250 kg before its 30s, while the lightest dolphin weighs only 82 kg when it is two years old.

Among the three regression models, the relationship between age (in years) and average weight (in kg) of common bottlenose dolphins presents the highest correlation, with an R^2 value of 0.33. This suggests that older dolphins tend to have larger body sizes.

3.3. Age and body weight negatively influence energy consumption

It was indicated before that increasing age and higher body weight during adulthood can negatively influence energy consumption requirements in bottlenose dolphins, likely due to metabolic changes and higher maintenance costs, respectively [16]. In this investigation, a similar trend was observed that aligns with the previous conclusion. As depicted in Figure 6, there is a negative correlation between the age (in years) of common bottlenose dolphins and their energy requirement (in Kcal/kg/day), represented by the regression equation y = 79.74 – 0.99x. Generally, common bottlenose dolphins younger than 20 years old have higher energy requirements than those older than 20 years old. However, the fitness of the correlation is not high ($R^2 = 0.11$), this might be due to the following reason: Lactating female dolphins have significantly higher energy requirements, consistent with previous studies; the data in this research also includes subadult males, which might also have a negative influence on the fitness of the data points to the trend [2].

As illustrated in Figure 7, there is a negative correlation between the average weight (in kg) of common bottlenose dolphins and their energy requirement (in Kcal/kg/day), with the regression equation y = 121.90 – 0.34x. This indicates that larger dolphins require less energy per kilogram of body weight compared to smaller, lighter dolphins. Several data points from lactating female dolphins, who, despite having similar weights to others, require much more energy could be considered outliers in the following study. Eliminating those data of lactating females could significantly increase the R^2 value.

4. Discussion

This investigation reveals a general pattern across several similar research, contributing to further understanding of nutrient supply of captive common bottlenose dolphins. The positive correlation between the age and average weight of bottlenose dolphins coincides with the expectations and aligns with previous studies [3]. This relationship indicates that, as dolphins age, they tend to gain weight, reflecting their growth and development stages. Although the body size of common bottlenose dolphins varies depending on age, energy intake, and habitat, they generally reach a weight threshold between 200 and 250 kg. Most common bottlenose dolphin in captivity falls within the range of 150 to 200 kg [6]. The weight threshold suggests that while dolphins continue to grow with age, their weight stabilizes as they reach adulthood. The negative correlations observed between age and energy requirement, as well as weight and energy requirement, are also consistent with findings from previous studies [17]. As common bottlenose dolphins age, they exhibit a decrease in energy requirements, and heavier dolphins typically require less energy per kilogram than their lighter counterparts. These findings are consistent with previous research, affirming that data from dolphins at various developmental stages and conditions reflect accurate trends. However, the weaker correlations observed highlight the complexities of how age, weight, and reproductive status interact to influence energy needs.

During data collection and analysis, several limitations were encountered. Firstly, inconsistency in data reporting among the three studies, with some data directly listed in tables while others required extraction from graphs, increased the risk of errors during interpretation. Additionally, variations in geographic locations and periods of the studies, spanning from 1965 to 1995, introduced variability due to differing environmental conditions and measurement techniques [13]. Furthermore, the inclusion of

diverse dolphin populations, such as subadult, adult, pregnant, and lactating dolphins, added complexity to the analysis, with lactating females notably exhibiting significantly higher energy requirements and thus affecting the correlation coefficient. However, each growth stage data sample number is not high enough to conduct a trustworthy analysis of each development phase. Additionally, the simplified method of recording age and using equations to estimate weight assumed consistent growth patterns, potentially overlooking individual variations. Finally, the linear modeling method used may not fully capture the complexities in the relationships between age, weight, and energy requirements. Including a more complex model might introduce a higher fitness among these three factors.

There are more factors that can be included in a complex fitness model, such as the activity level of common bottlenose dolphins. However, there are a few studies that described this category for wild bottlenose dolphins and only some for those in captivity [18].

To advance and refine future studies, the following aspects can be considered. First of all, it is imperative to gather a more extensive range of data samples from common bottlenose dolphins worldwide to provide a better general perspective for captivation. Secondly, adopting a consistent methodology for measuring the body size and energy requirements of bottlenose dolphins across studies can significantly eliminate human error in measurement. Additionally, maintaining consistency in the types of food used to feed all dolphins involved in the research is also crucial for ensuring a constant energy intake. Furthermore, lactating and pregnant female dolphin samples should be documented separately, as this special body condition can significantly skew the analysis result. By standardizing these methods and expanding the scope of data collection, future studies can achieve greater accuracy and comprehensiveness in their analyses.

5. Conclusion

This article underscores the significance of comprehending the physical characteristics and energy requirements of captive common bottlenose dolphins, offering valuable insights applicable to both research and practical feeding strategies. Age and weight negatively influence the energy consumption of dolphins, and age vs weight are positively correlated with each other. This research illustrates how including subadult male and female dolphins, pregnant and lactating female dolphins affects data analysis and the correlations among age, weight, and energy requirement, urging researchers to consider sample composition carefully. To enhance future studies, it is recommended to employ standardized methodologies for measurement and sample selection, along with broader data sources. This approach ensures accuracy and representativeness, thereby advancing people's understanding of dolphin physiology, aiding conservation efforts, and enhancing welfare practice.

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Appendices

Table 1. The original record of individual dolphins' age, average weight, and energy requirement from literature. +-number indicates a range from the average number, bracket after the energy requirement indicates a standard error from the raw data.

Literature resources	Identity	Age (y)	AVG Weight (kg)	Energy requirement (Kcal/kg/d)	Food consumption (kg/y)	Date of recording	Fish type
Reddy *et al.,* 1994	Tt646	6	152	81(12)			

Table 1. (continued).

yellow = subadult males	Tt748	11	128+/-6	66(8)		
red = adult males	Tt757	13	157+/-9	53(9)		
light blue = subadult females	Tt490	19	191+/-6	62(12)		
dark blue = adult females	Tt000	28	250+/-6	34(3)		
brown = pregnant females	Tt649	5	118	71(11)		
green = lactating females	Tt615	7	173	56(12)		
	Tt762	9	150+/-9	58(10)		
	Tt753	11	149+/-9	61(12)		
	Tt657	11	129+/-7	73(8)		
	Tt497	14	165+/-11	54(11)		
	Tt677	15	150+/-8	67(12)		
	Tt043	29	199+/-8	38(5)		
	Tt004	33	217+/-7	39(7)		
	Tt615	11	219	47(5)		
	Tt657	11	123	89(18)		
	Tt677	14	150	79(7)		
	Tt497	16	170	65(8)		
	Tt001	18	157	51(4)		
	Tt453	22	188	36(6)		
	Tt615	12	219	105(15)		
	Tt657	12	123	153(6)		
	Tt677	15	150	103(26)		
	Tt497	17	170	105(22)		
	Tt001	19	157	104(14)		
	Tt453	23	188	88(14)		
Kastelein et al., 2002	TtWS001	24	179	41	1600 kg/y	before 1991	65% herring+30% mackerel+5% squid
	TtWs005	16	226	47	2300 kg/y	before 1991	65% herring+30% mackerel+5% squid

Table 1. (continued).

	TtWs006	6	153	57	1900 kg/y	before 1991	65% herring+30% mackerel+5% squid
	TtWs007	4	142	65	2000 kg/y	before 1991	65% herring+30% mackerel+5% squid
	TtWs008	3	193	55	2200 kg/y	after 1991	60% herring+40% mackerel
	TtWs002	20	209	53	2400 kg/y	before 1991	65% herring+30% mackerel+5% squid
	TtWs003	20	209	46	2100 kg/y	before 1991	65% herring+30% mackerel+5% squid
	TtWs010	2	82	77	1300 kg/y	after 1991	60% herring+40% mackerel
Kastelein *et al.,* 2005	TtZH006	31	189	46	1875 kg/y	1993	30% herring+30% mackerel+15% whiting+20% sprat+5% squid
	TtZH010	10	182	44	1750 kg/y	1993	30% herring+30% mackerel+15% whiting+20% sprat+6% squid
	TtZH007	31	177	46	1750 kg/y	1993	30% herring+30% mackerel+15% whiting+20% sprat+7% squid
	TtWS005	19	221	47	2270 kg/y	1993	30% herring+30% mackerel+15% whiting+20% sprat+8% squid
	TtWS007	8	160	58	2000 kg/y	1993	30% herring+30% mackerel+15% whiting+20% sprat+9% squid