Philips CoralCare LED unit

Final Field Test Report

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Produced by Tim Wijgerde, Ph.D., Coral Publications. Commissioned by Philips Advanced Development Europe, Philips Lighting.

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Summary

This report presents the definitive results obtained during a field test of the CoralCare LED unit developed by Philips Lighting. The goal of the field test was to evaluate the performance of the CoralCare unit as a light source for marine aquaria, in particular corals. Two 190W CoralCare units were placed above a 490L aquarium (dimensions 200 x 70 x 35 cm), as well as two T5 reference luminaires (ATI Sunpower, 6x54W dimmable each). The aquarium was divided into two sections using a PVC separator, to prevent cross–over effects of each light source. Quantum irradiance (photosynthetically active radiation, ~400–700 nm) was set to ~560 µmol photons m^{-2} s^{-1}. Water flow was created by placing one flow pump (Maxspect Gyre 150) in each section, operating at 20% power at constant forward flow, resulting in a water flow rate of 10–15 cm s^{-1} around the corals. In each section, four scleractinian coral species (N=5 fragments per species per light source) were cultured; a pink morph of *Stylophora pistillata*, a purple and blue *Acropora* sp., and a green *Acropora cf. muricata* (N_{total}=40 fragments). The performance of both light sources was evaluated by measuring the specific growth rate of each coral species, as well as by subjective photographic analysis of their morphology and colour for a six–month period. No significant growth differences between T5 and CoralCare LED were found for any of the species, although growth differences between species were detected, irrespective of light source. Subjective evaluation of photographs suggests that coral health and morphology are similar between light sources after 188 days of culture, with slightly enhanced coral colouration under CoralCare LED. In conclusion, the CoralCare unit developed by Philips Lighting is the first LED–based product with proven similar results as T5 lighting, the current market standard. In addition, the CoralCare LED constitutes a significant step forward in terms of improved energetic efficiency.

Introduction

This report presents the definitive results obtained during a field test of a new LED unit developed by Philips, entitled CoralCare. The aim of the field test was to determine the performance of the new LED unit as a light source for marine aquaria, in particular scleractinian (stony) corals.

Proper lighting is one of the key aspects when maintaining a marine aquarium with corals and reef fishes. First, light is essential to the growth of reef–building corals. These corals are host to symbiotic dinoflagellates known as zooxanthellae, which use light energy for photosynthesis, a biochemical process in which carbon dioxide (CO_2) and bicarbonate (HCO_3^-) are converted to organic compounds such as glycerol, carbohydrates, fatty acids and amino acids. These compounds are in part translocated to the tissues of the host coral, which uses these for growth and metabolism (Muscatine et al. 1981; Muscatine 1990; Furla et al. 2005). In addition, light is important to create a photoperiod in the aquarium, i.e. a day/night simulation. This stimulates the natural behaviour of fishes and other aquarium life.

When regarding light for aquaria, three factors are important; light intensity (irradiance), spectral distribution and light distribution. For corals specifically, sufficient light intensity is required to stimulate photosynthesis and growth, and in particular colouration (Muscatine et al. 1981; Muscatine 1990; D'Angelo et al. 2008). For corals of the genus *Acropora*, for example, an irradiance of at least 700 µmol photons m^{-2} s^{-1} as photosynthetically active radiation (PAR, ~400–700 nm) is required to fully saturate host pigmentation (D'Angelo et al. 2008). In terms of spectrum, sufficient blue radiation is required to evoke healthy zooxanthellae and coral growth, and chlorophyll synthesis (Kinzie et al. 1984, 1987; Wang et al. 2008; Wijgerde et al. 2014). In addition, to properly visualise the colours of all aquarium life, all wavelengths must be present in a given spectrum. This means that the "ideal" light spectrum for the average marine aquarium is continuous, with a blue peak to create a natural effect. This is comparable to a seawater depth of approximately 10 meters, where all colours are still found, but with decreased presence of red and orange. This is due to the fact that seawater selectively attenuates sunlight, with light of longer wavelengths being filtered more effectively (Mass et al. 2010). The CoralCare LED unit provides such a spectrum with high colour rendering, well–suited for marine life. Next to high colour rendering, marine aquarists seek a homogeneous light source, which is beneficial to the aquarium's inhabitants as well as aesthetically pleasing. A subset of aquarists also seeks a dynamic shimmer effect, which mimics a sunny day on a coral reef. In this respect, Philips has found an optimum between homogeneity and natural shimmer by designing special patented optics.

To determine the suitability of the new CoralCare LED unit, subjective field tests were performed at various locations, with the assistance of several aquarium hobbyists. In addition, a more scientific field test was conducted, for which the following research question was formulated:

What is the performance of the CoralCare LED unit, in terms of stimulating coral growth, colouration and morphology, compared to traditional T5 technology?

To address this question, coral growth was measured by weighing corals cultured under T5 reference luminaires and Philips CoralCare LED units. In addition, corals were photographed to document their health, colouration and morphology.

Materials and Methods

Culture system

The experiment was performed at a private residence, where a complete Berlin system was in operation. This system consisted of a main display aquarium, with dimensions 300 x 100 x 85 cm (length x width x height), a filtration sump (dimensions 120 x 60 x 60 cm) and an aquarium for maintaining coral fragments (dimensions 230 x 70 x 30 cm). The total system volume was 3,465 liters. The main filtration unit was foam fractionator (Bubble King 400 internal with ozonator, Royal Exclusiv, Köln, Germany). A DIY calcium reactor was used to maintain stable calcium, magnesium and alkalinity/KH levels. Trace element additions were done regularly to maintain natural trace element levels. A return pump (ATK–MP1206, 12 m^3 $hour^{-1}$, Aqualight GmbH, Bramsche/Lappenstuhl, Germany) constantly exchanged water between the three basins. The coral experiment was conducted in the refugium (see below).

Experimental setup

Two 190W CoralCare units were placed above the refugium (see above), in addition to two T5 reference luminaires (ATI Sunpower, 6x54W dimmable each, with a total of twelve Aquablue Spezial 12,000 Kelvin bulbs). The aquarium was divided into two sections using a PVC separator panel, to prevent cross–over effects of each light source (Figure 1). Spacings on both sides of the PVC panel allowed water to flow freely between both compartments. A small circulation pump (Nanostream 6020, Tunze, Penzberg, Germany) was added to promote water exchange between the compartments.

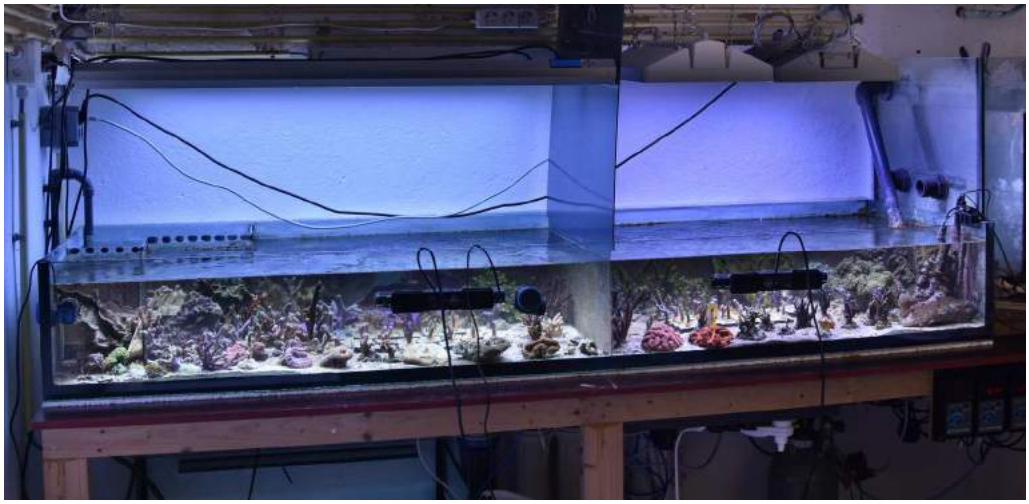

Figure 1: Overview of the experimental setup.

Irradiance

Irradiance was measured at 5 cm space intervals at the water depth of the corals using a LI–COR LI–192SA quantum underwater sensor with computer (LI–COR, Lincoln, USA), which measures photosynthetically active radiation (PAR, ~400–700 nm). For both setups, PAR was set to ~560 µmol photons m^{-2} s^{-1} (Figure 2). Only the areas in which the corals were placed were measured for PAR levels and plotted.

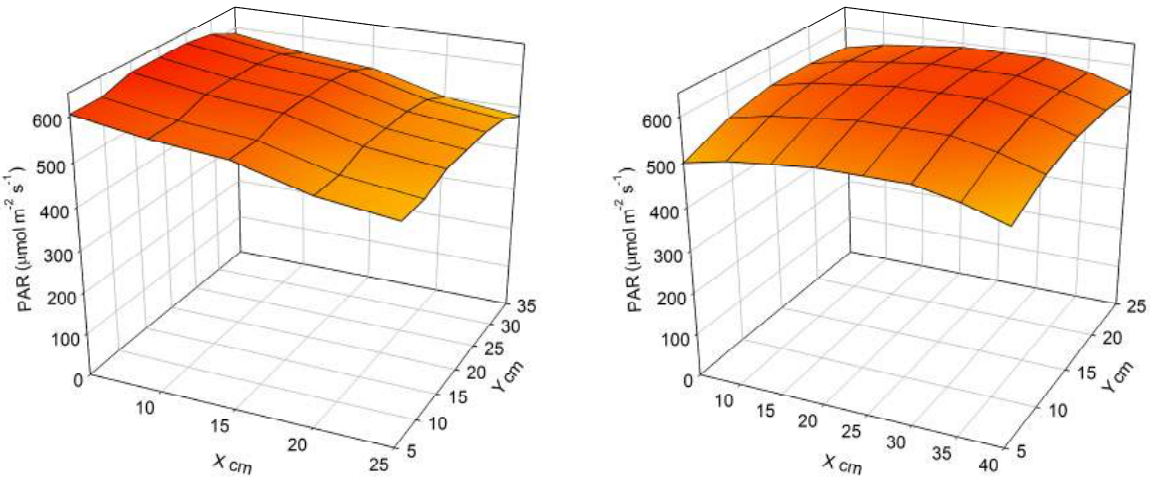

Figure 2: PAR landscape of the T5 luminaires (left) and the CoralCare LED units (right) as seen from the front of the experimental setup. Mean PAR values of the T5 luminaires and CoralCare LED units were 561±42 S.D. and 565±29 S.D. µmol m^{-2} s^{-1}, respectively. Only the areas in which the corals were placed are plotted. Note that corals within both treatments were rotated weekly to cancel out local PAR variations.

Spectral output

The spectral data of both light sources were determined by individually placing both fixtures in an optical measurement sphere at the Philips laboratory (Figure 3). The Aquablue spezial bulbs emitted full spectrum light (Figure 4) with four large peaks in the violet (405 and 436 nm), green (546 nm) and orange (611 nm) spectral regions. The CoralCare LED, when set at a similar colour point as the T5 fixture, emitted a broad violet/blue peak (425–460 nm) and a smooth curve up to the red spectral region (700 nm).

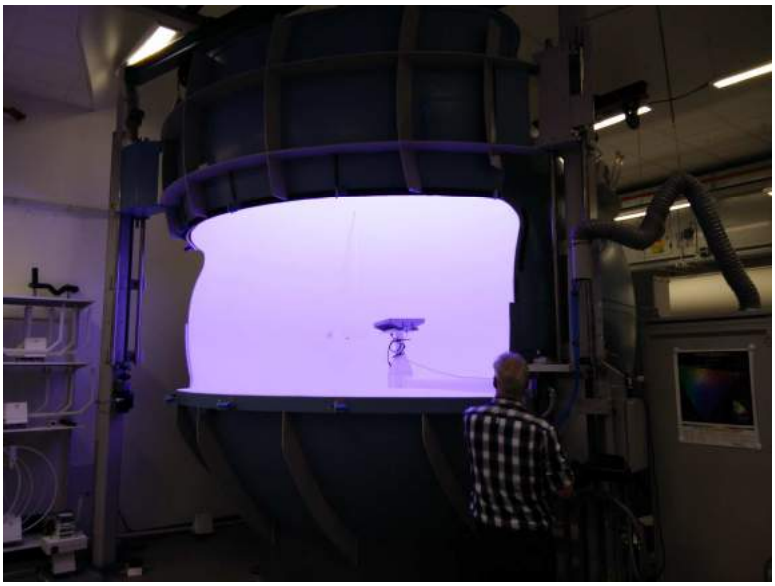

Figure 3: The optical measurement sphere at Philips, used to determine the wall–plug efficiency of both light sources. Only the CoralCare LED unit is shown here. During measurements, the sphere is completely closed to measure all light emitted by the source.

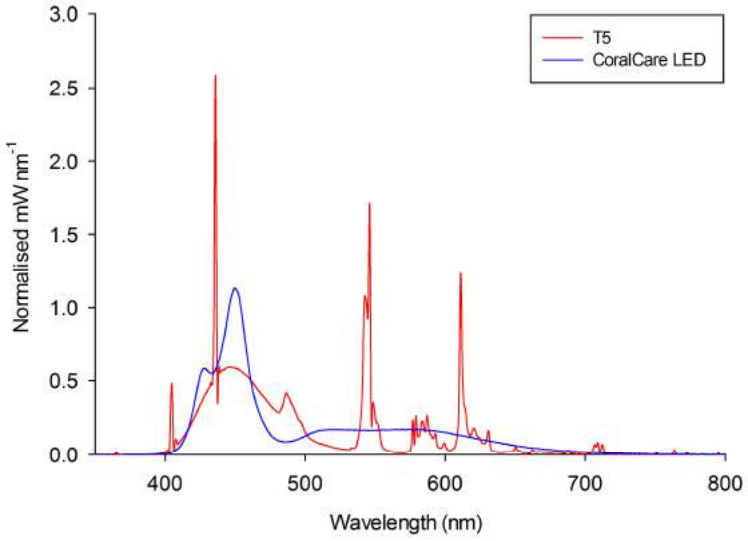

Figure 4: Spectral data of the T5 and CoralCare LED fixtures used in this study. Note that the CoralCare LED has a variable spectral output and colour point. For this study, the colour points of both light sources were set as similarly as possible.

Colour point

The colour point of light is standardised in a CIE 1931 colour space with a normalised x–y coordinate system, which translates the contribution of all spectral wavelengths in a unified coordinate on a colour diagram. With such a diagram, a given colour, but also the difference between colours can be described.

When six Aquablue Spezial 12,000K bulbs are mounted, as in this experiment, the conventional T5 luminaire operates with a colour point of x=0.238, y=0.202 (Figure 5). This configuration was chosen to match previous coral experiments (Wijgerde et al. 2014; Hylkema et al. 2015), allowing for better comparison. The CoralCare unit is able to produce a range of colour points between x=0.151, y=0.021 (CoralCare #1) and x=0.317, y=0.337 (CoralCare #2, Figure 5). To allow for a fair comparison between the two light technologies, the colour point of the Philips CoralCare unit was matched to the T5 luminaire as closely as possible. This was done by setting channel 1 to 60%, and channel 2 to 100%, which is perceived as a rather "warm" colour point by marine aquarists.

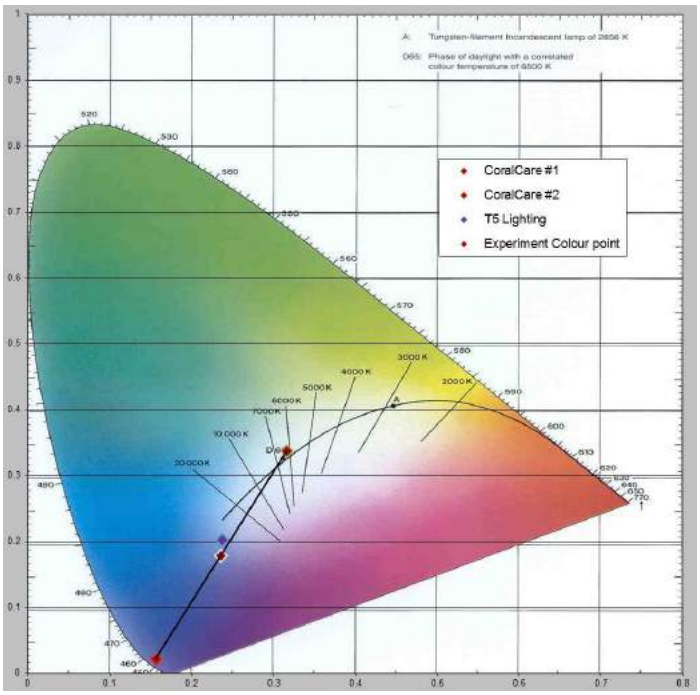

Figure 5: CIE 1931 x–y chromaticity space of both light sources, with T5 represented by a purple diamond, and the CoralCare LED by red diamonds. The red diamond in the middle of the black line, close to the purple T5 diamond, represents the LED colour point used in this experiment.

Wall–plug efficiency

Wall–plug efficiency (or radiant efficiency) is a key aspect of a light source, which is defined as the amount of light (optical power or radiant flux) generated from the ingoing electrical power. For instance, an incandescent light bulb converts only 2.1% of its input power to optical power, whereas the remaining energy is converted to heat. With an optical measurement sphere at the Philips laboratory, all key

parameters were measured to calculate wall–plug efficiencies of the T5 luminaires and the CoralCare LED units.

Please note that the T5 and CoralCare LED units above the coral setup were dimmed to create an equal irradiance between both light sources, within two defined regions where the coral samples were placed. In addition, T5 and CoralCare LED emit light in a different pattern and area. Thus, the total available power above the setup (648W for T5 and 380W for CoralCare LED), even when taking the dimming factor into account, cannot be used to calculate wall–plug efficiency. This is only possible using the optical measurement sphere shown in figure 3, which measures the total amount of light emitted by the fixtures, at all wavelengths and directions.

Water flow and water quality

Water flow was created by placing one flow pump (Maxspect Gyre 150, 60W) in each section, operating at 20% power at constant forward flow. Water flow was measured with a current velocity meter (Model 2100, Swoffer Instruments, Seattle, USA) and recorded at 10–15 cm s^{-1} around the corals.

Water quality was measured weekly using home test kits (Salifert BV, Duiven, The Netherlands). In addition, a broad elemental analysis using ICP–OES was performed once at a commercial lab. Temperature was maintained at 24°C, salinity at 35 g L^{-1} (ppt) and pH at ~8.

Corals

In each section, four scleractinian coral species (N=5 fragments per species for each light source, N=40 fragments in total) were cultured; a pink morph of *Stylophora pistillata* (Esper 1797), a purple and blue *Acropora* sp. (Oken 1815), and a green *Acropora cf. muricata* (Linnaeus 1758, obsolete synonym *A. formosa* Dana 1846). The blue *Acropora* sp. was added to the experiment 24 days after the initial experiment had started, to gain more insight into the response of light–demanding *Acropora* spp. All fragments within a given species originated from the same parent colony, i.e. they were genetically identical to rule out intraspecific variation. All corals were glued onto 5x5 cm Trespa tiles using two–component epoxy resin (Tunze Aquarientechnik GmbH, Penzberg, Germany). Each tile was labelled with a unique number. After fragmentation, coral samples were randomly assigned to either the T5 or LED treatment, to prevent a possible selection bias for either treatment. Under each light source, all corals were rotated weekly within their group to cancel out potential local variations in irradiance, spectrum and water flow rate. This was done by shifting the corals in each column towards the back of the aquarium one step at a time. First, the displaced coral in the back of the column was transferred to the front of the column on the right. This column was again shifted towards the back, after which a newly displaced coral was transferred to the front of another column on the right. Finally, the last coral to be displaced was returned to the front of the first column. This method ensured that each coral changed position every week.

Figure 6: In both sections of the setup, corals were placed randomly and rotated weekly within their group to cancel out local variations in irradiance, spectrum and water flow rate. Left: T5, right: CoralCare LED. Shown are the four species at the end of the experiment.

Specific growth rate

Corals were weighed at the start of the experiment, and subsequently once a month, over a period of six months using a laboratory scale (U 4600p, Sartorius, Goettingen, Germany). Each coral fragment was weighed before and after being glued onto its Trespa tile, to determine the combined weight of the tile and glue. For each weighing point, the corals were removed individually from the aquarium, tiles were carefully cleaned with a small brush and dried with a cloth, and total weights were obtained. To calculate net coral weights, the combined weight of each coral's tile and glue was subtracted from the total weight. In addition, the effect of water uptake by Trespa tiles on their weights was determined. To this end, Trespa tiles of representative dimensions (N=5) were incubated in seawater for 3.5 weeks, which resulted in an average mass increase of 1.09±0.12 grams. All growth data were subsequently corrected for this artifact. To calculate specific growth rates (SGR) for each individual, a first order kinetics exponential growth model was used (Wijgerde et al. 2012):

$$SGR\ (day^{-1}) = ln\ (W_T / W_{T-1}) / \Delta t$$

where W_T is the net weight of a given coral expressed in grams (g) at the end of an interval, W_{T-1} is the net weight of a coral in grams (g) at the start of an interval, and Δt is the growth interval in days. SGR is expressed in gram coral gram coral^{-1} day^{-1}, which can be simplified as day^{-1}. When SGR is multiplied by 100, the daily percent growth in coral biomass is obtained. As branching corals bifurcate continuously, they increase their growing surface area over time. Thus, the amount of biomass they produce every day increases with time. In other words, branching corals do not grow linearly, but exponentially (Leal et al. 2014). For this reason, the natural logarithm *ln* is used in the formula, which takes this exponential growth of branching corals into account.

Health, colouration and morphology

For subjective analysis of coral health, colouration and morphology, a photographic setup was used (Figure 7). All corals were photographed at the start of the experiment and about once per month, over a period of six months. A Nikon D700 with Nikkor 70–180 mm micro lens (Nikon Corporation, Tokyo, Japan) was used for all photographs. All camera settings, including zoom factor, were kept constant. White balance was manually corrected using Capture NX–D (Nikon Corporation, Tokyo, Japan). Note that the fluorescent light source used (38W, Diamant, Budel, The Netherlands) emitted white light with a relatively low colour temperature of 6400K, making the corals in Figures 10 to 12 appear differently when compared to the actual T5 and LED setups (Figure 6). To further determine the effect of light source on coral colouration, randomly selected colonies of each species from both light sources were photographed under a blue/white light source (Apollo 4, OEXDE, China), which excites and visualises the fluorescent pigments of the corals.

Figure 7: The 6400K setup used to photograph the corals. A ruler was used for scale.

Statistical analysis

Normality of specific growth data was evaluated by plotting residuals of each dataset versus predicted values, and by performing a Shapiro–Wilk test. Homogeneity of variances was determined with Levene's test. All data were found to be normally distributed and showed homogeneity of variance after a square root transformation ($p>0.050$), allowing the use of a parametric ANOVA. A two–way factorial analysis of variance (ANOVA) was used to determine the main and interactive effects of light source and species on coral specific growth rate. A Bonferroni *post–hoc* test was used to determine growth differences between coral species. Statistical analysis was done with IBM SPSS Statistics 22 (IBM Corp., Armonk, USA). Graph plotting was done with SigmaPlot 12.0 (Systat Software, Inc., San Jose, USA).

Results, Discussion and Conclusion

Wall–plug efficiency

Table 1 lists the electrical power, optical power and wall–plug efficiency of the T5 luminaires and CoralCare LED units. Using the settings of this experiment, the CoralCare LED units generate a similar colour point compared to T5 at 30% (or 7.3 percentage point) higher efficiency (i.e. 32% versus 24.7% WPE for LED and T5, respectively).

Table 1: Electrical power (P_{elec}) and optical power ($P_{optical}$) measured in Watts (W), and wall–plug efficiency (WPE) of the T5 luminaires and CoralCare LED units. WPE values in bold are representative for the experiment.

Fixture	**P_{elec} [W]**	**$P_{optical}$ [W]**	**WPE [%]**
T5	386.7	92.4	23.9
T5 dimmed to test value	273.2	67.5	**24.7**
Philips CoralCare	189.7	60.4	31.9
Philips CoralCare set at test colour point	158.1	50.6	**32.0**

Water quality

Water chemistry was close to natural conditions (Spotte 1992), although phosphate was elevated compared to pristine coral reefs (Tanaka et al. 2007). No elevated levels of potentially toxic trace elements, such as chromium, copper or aluminium were found. Table 2 shows water quality during the experiment.

Table 2: Water quality during the course of the experiment. Values are means ± s.d. (N=1–8).

Parameter	**Value**
Sodium (mg L^{-1})	10,513
Magnesium (mg L^{-1})	1,399±27
Sulphur (mg L^{-1})	803
Calcium (mg L^{-1})	427±10
Potassium (mg L^{-1})	396
Bromine (mg L^{-1})	50.59
Strontium (mg L^{-1})	10.85
Boron (mg L^{-1})	4.62
KH (°DH)	7.3±0.5
Alkalinity (mEq L^{-1})	2.60±0.18
Nitrate (mg L^{-1})	< 0.2
Phosphate (mg L^{-1})	0.027±0.015

Specific growth rate

After 33 days of culture, *Stylophora pistillata* exhibited similar specific growth rates under both light sources (Figure 8), equal to 1.95±0.26% and 1.99±0.36% day^{-1} for T5 and LED, respectively. The purple *Acropora* sp. also showed comparable growth under both light sources (Figure 8), with 1.37±0.23% day^{-1} under T5 and 1.44±0.18% day^{-1} under LED. The same was found for *Acropora cf. muricata* (Figure 8), with growth rates of 1.82±0.27% and 1.73±0.18% day^{-1} for T5 and LED, respectively.

After 188 days of culture, *S. pistillata*, the purple *Acropora* sp. and *A. cf. muricata* showed decreased daily growth rates (Figure 9). Despite this decrease, the same pattern was observed, with highly similar growth rates between light sources. Growth rates obtained under the T5 and CoralCare LED units were 1.13±0.03% and 1.09±0.04% day^{-1} for *S. pistillata*, respectively. For the purple *Acropora* sp., growth rates were 0.89±0.13% day^{-1} under T5 and 0.91±0.09% day^{-1} under CoralCare LED. *A. cf. muricata* exhibited growth rates of 0.76±0.10% day^{-1} and 0.87±0.11% day^{-1} under T5 and CoralCare LED, respectively. After 164 days, the blue *Acropora* sp. also showed comparable growth under both light sources (Figure 9), with growth rates of 0.78±0.14% day^{-1} under T5 and 0.81±0.11% day^{-1} under CoralCare LED. Up to this point, the survival rate of all four species was 100%.

Statistical analysis of the shorter 33–day interval revealed that the factor light source had no significant main or interactive effect on coral specific growth rates (Table 3). Thus, for each species, specimens cultured under T5 grew at an equal rate as those under LED. Species, on the other hand, did have a significant effect on growth rates (Table 3), with *Stylophora pistillata* and *Acropora cf. muricata* showing higher growth rates than the purple *Acropora* sp. (Bonferroni, P=0.000 and P=0.010, respectively), independent of the light source. No significant growth difference was found between *S. pistillata* and *A. cf. muricata* (P=0.296).

Analysis of the longer 164–188 day interval showed a similar pattern, with no significant effect of light source on growth of any species (Table 3). Species, again, did have a significant effect on growth rates (Table 3). *Stylophora pistillata* showed higher growth than the three *Acropora* spp. (Bonferroni, P=0.000 for all comparisons), regardless of light source. No significant growth differences between the three *Acropora* spp. were found (Bonferroni, P=1.000 for all comparisons).

A possible explanation for the lack of statistically significant growth differences between light sources is the resemblance of light intensity, colour point, spectrum and light distribution when comparing the T5 luminaires and CoralCare LED units (Figures 2 to 5). For example, both light sources emit a significant amount of voilet and blue light (~400–500 nm), which is known to play a key role in coral growth, colouration and photophysiology, promoting coral and zooxanthellae growth, fluorescent protein production, chlorophyll *a* synthesis and photosynthesis rates (Kinzie et al. 1984, 1987, D'Angelo et al. 2008, Wang et al. 2008; Mass et al. 2010; Wijgerde et al. 2014). However, subtle differences between the two light sources tested here could still result in long–term growth variations.

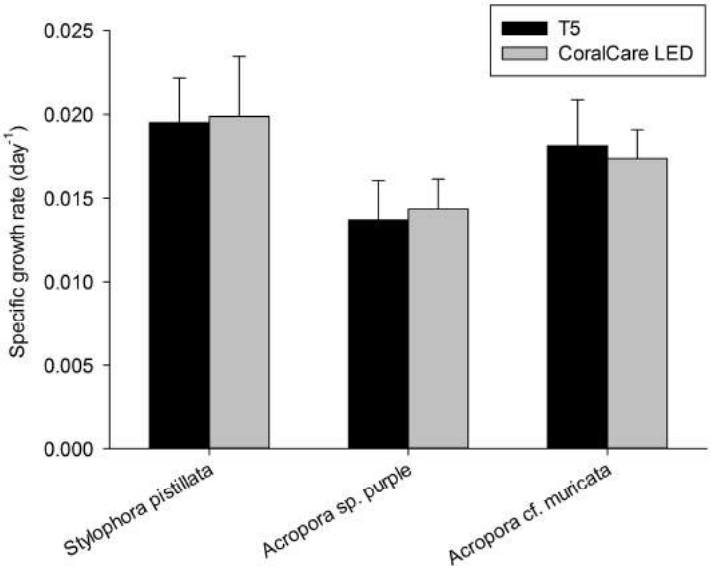

Figure 8: Specific growth rates of Stylophora pistillata, Acropora sp. purple and Acropora cf. muricata under T5 and CoralCare LED, at an irradiance of ~560 µmol m^{-2} s^{-1}. Growth interval was 33 days for all species. Data are means + standard deviation (N=5).

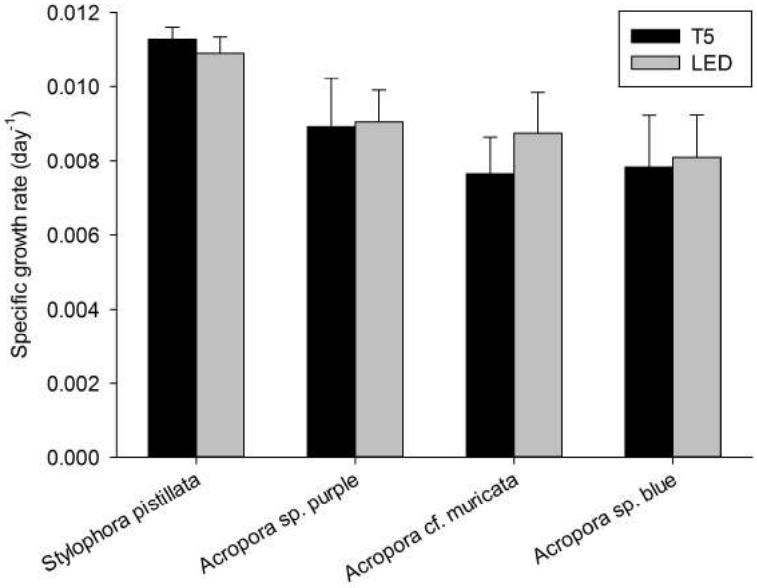

Figure 9: Specific growth rates of Stylophora pistillata, two Acropora sp. and Acropora cf. muricata under T5 and CoralCare LED, at an irradiance of ~560 µmol m^{-2} s^{-1}. Growth interval was 188 days for the first three species and 164 days for Acropora sp. blue. Data are means + standard deviation (N=5).

The observed growth rates over the entire experimental period ranged from 0.0076 to 0.011 per day (or 0.76 to 1.13% per day), and lie within the range found in the literature (Schutter et al. 2010; Wijgerde

et al. 2012; Wijgerde and Laterveer 2013). The growth rates presented here are lower than those from the preliminary report, which can be explained by two factors. First of all, the growth data presented here have been corrected for water uptake by the Trespa tiles used (see page 10), which previously resulted in an overestimation of growth rates. Secondly, slight necrosis around the base of most colonies (see page 17) is likely to have had a negative impact on growth rates.

Despite these issues, the growth rates presented here can be regarded as normal, and are associated with healthy corals. This is most likely due to the sufficiently high irradiance applied in this experiment, which is close to saturating photosynthesis and growth in scleractinian corals (Chalker 1981; Schutter et al. 2008; Wijgerde and Laterveer 2013), as well as proper water flow rate, which is equally important to coral growth (Schutter al. 2010, 2011). In addition, calcium, alkalinity, pH and temperature are also known to significantly affect coral calcification, which were maintained close to natural during this experiment (Spotte 1992), and therefore still within the growth–limiting range (Chisholm and Gattuso 1991; Marshall and Clode 2002; Carricart–Ganivet 2004; Hylkema et al. 2015).

Table 3: Two–way factorial ANOVA, showing main and interactive effects of light source and coral species on specific growth rate (SGR) after a 33 day and 164–188 day growth interval.

Factor	**Variable**	**F**	**df**	**error**	***P***
	SGR 33 day interval				
Light source		0.007	1	24	0.936
Coral species		12.870	2	24	0.000*
Light source * Coral species		0.236	2	24	0.791
	SGR 164–188 day interval				
Light source		0.814	1	32	0.374
Coral species		19.863	3	32	0.000*
Light source * Coral species		0.913	3	32	0.446

*Indicates significant effect ($P<0.050$).

Health, colouration and morphology

At the start of the experiment, all corals appeared healthy and exhibited similar colouration (Figure 10). No signs of bleaching or necrosis were observed. After 33 days of culture, all corals appeared healthy, and colonies grown under T5 lighting showed colouration comparable to those cultured under LED when photographed under 6400K white light (Figure 11).

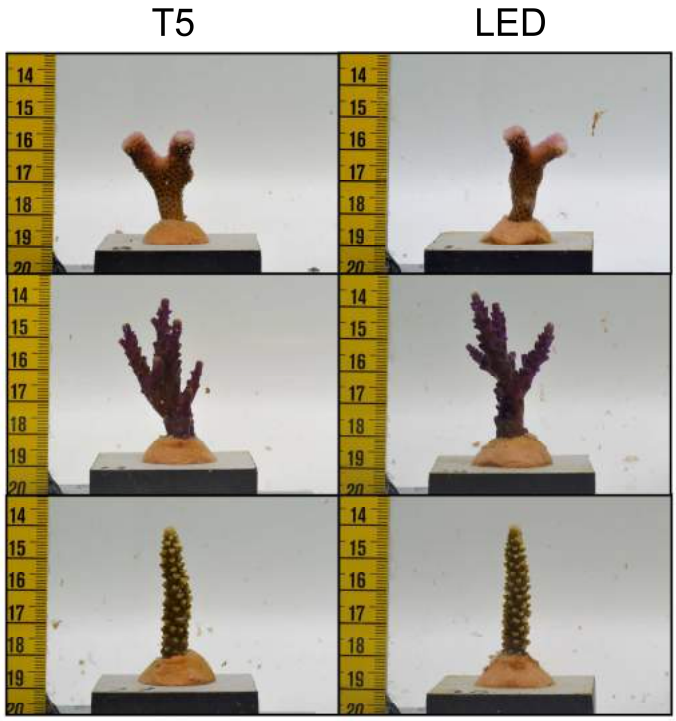

Figure 10: Representative photographs of Stylophora pistillata (top row), Acropora sp. (middle row) and Acropora cf. muricata (bottom row) at the start of the experiment. Scale bars depict centimeters.

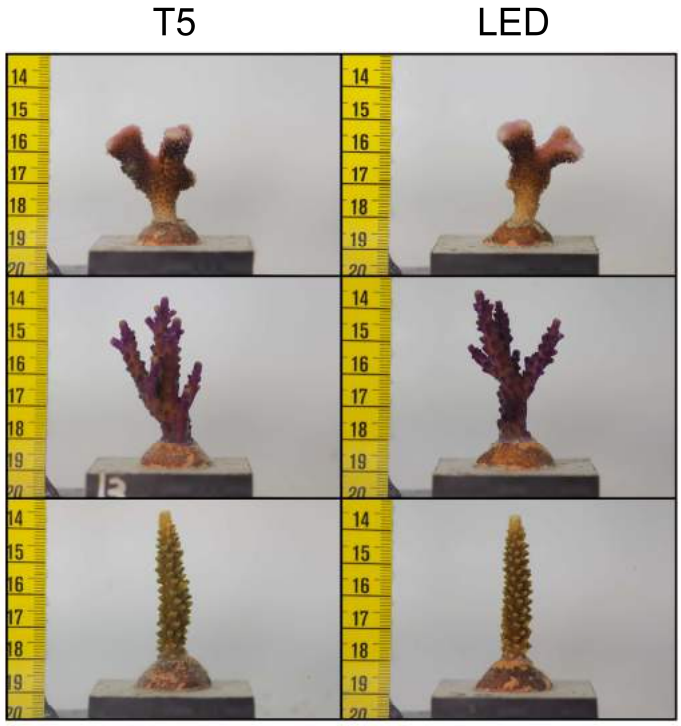

Figure 11: Representative photographs of Stylophora pistillata (top row), Acropora sp. (middle row) and Acropora cf. muricata (bottom row) cultured under T5 or CoralCare LED after 33 days. All corals were photographed under 6400K white light. Scale bars depict centimeters. Note that the same individuals were photographed to allow comparison with the previous figure.

However, after about two months, all species were affected by cyanobacterial growth around the base of the colonies, which occurred under both light sources. Although cyanobacteria were regularly removed by carefully applying a tooth brush, this could not prevent slight tissue necrosis at the base of most colonies. This was most prominent for *S. pistillata* and *A. cf. muricata* (Figure 12). Interestingly, the purple and blue *Acropora* spp. did not seem to suffer much from the cyanobacteria, and started growing their colony base over the epoxy resin (Figure 12).

After the end of the experiment (164 to 188 days, depending on species), *S. pistillata* and the purple and blue *Acropora* spp. appeared healthy, with no signs of further necrosis for *S. pistillata*. *Acropora cf. muricata* appeared healthy overall, but slight necrosis and/or bleaching of the colony base remained, under both light sources (Figure 12). After 164 to 188 days, colouration of all four species was similar between T5 and CoralCare LED when photographed under 6400K white light (Figure 12). As branched coral colonies affect their own light microenvironment due to self–shading (Wangpraseurt et al. 2014), they influence their own colouration. This was apparent for all species under both T5 and LED, with brighter colouration at the upper parts of the colonies.

Figure 12: Representative photographs of Stylophora pistillata (top row), Acropora sp. purple (second row from the top), Acropora cf. muricata (middle row) and Acropora sp. blue (fourth row from the top) cultured under T5 or CoralCare LED. Images were taken after 188 days for the first three species, and after 164 days for Acropora sp. blue, under 6400K white light. Scale bars depict centimeters. Note that the same individuals of the first three species were photographed to allow comparison with the previous two figures.

When photographed under a light source with higher emission in the blue spectral region, subtle color differences between corals became apparent. All species showed slightly brighter coloration under the CoralCare LED (Figure 13). This is possibly due to the higher output of the CoralCare LED in the blue spectral region, around 450 nm (Figure 4), which is known to induce long–term colour changes in corals (D'Angelo et al. 2008). At higher blue irradiance, many stony corals increase their synthesis of non–fluorescent chromoproteins (dominant in *Stylophora pistillata*) and fluorescent proteins (abundant in *Acropora* spp.). This possibly concerns a photoprotective response, where corals shield their zooxanthellae from excess and harmful blue radiation. An important caveat here is that the T5 fixtures contained only "white" 12000K bulbs, which emit a limited amount of blue light, whereas hobbyists usually use a combination of white and blue bulbs. However, if such a T5 spectrum with a higher blue content would have been used, the most comparable colour point of the CoralCare LED would still have resulted in higher emission around 450 nm, possibly coupled to slightly brighter coral colouration, when compared to T5.

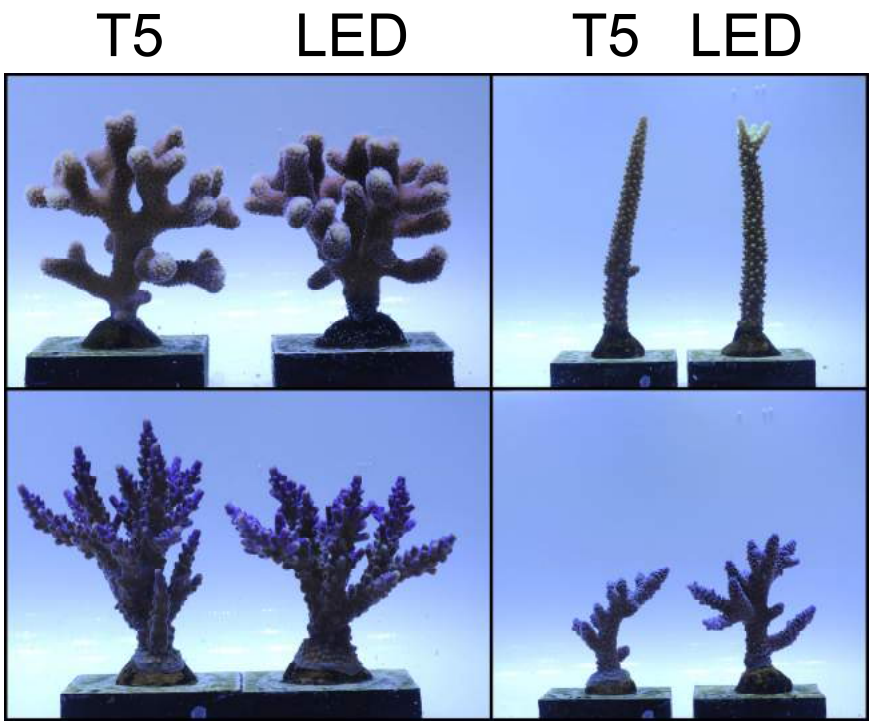

Figure 13: Representative photographs of randomly selected Stylophora pistillata (top left), Acropora sp. purple (bottom left), Acropora cf. muricata (top right) and Acropora sp. blue (bottom right) cultured under T5 or CoralCare LED. Images were taken after 188 days for the first three species, and after 164 days for Acropora sp. blue, under blue/white light. Note that individuals differ from the figures above, and that images between species are not to scale.

Morphology was also similar when comparing T5 and LED. *S. pistillata* and the purple *Acropora* sp. had formed their typical branched structures, under both T5 and LED. *Acropora cf. muricata* showed limited branching within the experimental period, under either light source, as it builds large, arborescent structures which take more time to develop. Therefore, evaluating the morphology of this species under

both light sources will require longer culture periods. The blue *Acropora* sp. colonies were too small to evualuate potential morphological differences. Although subtle morphological differences between colonies exist (Figures 12 and 13), these are possibly caused by random variations that existed from the start of the experiment (Figure 10). At present, there is no indication that gross colony morphology is significantly different between light sources, although long–term studies may reveal potential differences between T5 and LED. Coral micromorphology, such as corallite shape and size, and distance between corallites, has recently been found to be affected by light spectrum (Rocha et al. 2014). Therefore, it is possible that the CoralCare LED may induce subtle micromorphological differences when compared to T5 lighting.

Conclusion

The conclusion of this final field test report is that the CoralCare LED unit developed by Philips delivers results which are highly comparable to conventional T5 technology, at 30% higher wall–plug efficiency. Long–term use by aquarists is likely to substantiate the results presented in this report, in terms of coral health, colouration, morphology and growth rates.

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