

Lighting and the indoor microbiome: measuring the effect of LED lighting on E.coli

Lindsey Naganuma¹, Isaac Wimer¹

¹University of Oregon, Portland, Oregon

ABSTRACT: The more we learn about natural light's direct correlation to microbiology and its ability to regulate the production and growth of bacteria, the more the topic brings into question the effect electric light has on indoor microbiomes of the built environment. This research study specifically looks at the effects of different LED light spectrum wavelengths and their effect on *Escherichia coli* (E.coli) bacteria growth. Three residential LED lamps were used to expose plated E.coli to a range in spectrum of three different controlled LED lighting systems, as well as daylighting and their individual effects on the growth of E.coli over the course of 48 hours. The results indicated that LED lighting with high levels of orange and blue light were equally more effective at reducing the viability of E.coli colonies than the daylight levels during the study. Then those results were compared to the light spectrum readings of different artificially light spaces in the Scott Edwards Architecture office.

KEYWORDS: indoor, office, microbiome, LED, lighting

INTRODUCTION

As humans spend more time inside and building enclosures are more frequently designed as airtight systems that separate occupants further from the outdoors, the indoor microbiome of the built environment is becoming increasingly important to research and understand due to its effect on human health and wellbeing. Among a multitude of other effects on the human body, the transfer of microorganisms from the built environment to the occupant's cutaneous or mucosal membranes has the potential to disrupt immuno-regulations and/or exaggerate or suppress inflammation (Hoisington et. al., 2015). There is mounting evidence that the indoor lifestyle simplifies the microbial environment and with fewer pathogens to fight off during human immune system development, the resultant may create people who are more susceptible to getting sick or developing autoimmune disorders (Lax 2015).

Natural daylight within the built environment plays a role in the community and composition of indoor microbiomes due to its ability to regulate growth of certain bacteria. Today's energy conservation demands of the built environment typically force the building enclosure to minimize its glazing-to-solid wall percentage thereby drastically limiting the amount of daylight that enters indoor spaces. As direct response, buildings are increasingly utilizing the efficiency of LED technology to solve these problems. However, little study has been conducted on the effect electric lighting has on microbiology. Most of the research conducted on microbial built environments is surrounding natural daylight. One study looked at household dust's bacterial communities and the effect of light exposure on those communities. The experiment shows that light exposure affects the growth and survival of bacteria in dust communities (Fahimipour, 2018). Fahimipour et al. determined that the visible as well as ultraviolet spectra in daylight had similar results on bacteria indoors. By confirming that daylight kills certain bacteria, there is a direct link to building design and a healthy microbiome for the space. Designers directly have an impact on how much daylight the occupants of the building will receive.

There is only emerging research on microbiomes in the built environment, but one study looking at buildings as complex ecosystems found a relationship between building design, biodiversity and human health (Kembel 2012). This relationship was supported by the correlation between building attributes and airborne bacterial communities. Although, despite initial thoughts, ventilation changes did not significantly affect the level of human pathogens in the air.

Substantial research has been conducted on the effects of electric light on humans. There is strong evidence correlating the way light operates through the visual system and visual comfort (Boyce 2010). Additionally, it

is important to monitor the color and intensity of the lighting as there is a connection to the circadian system which influences sleeping patterns (Boyce 2010). While these findings are interesting and important, there is very little research about the effects of electric lighting on the microbial environment of built space.

In order to fully understand the impact energy efficient buildings and spaces have on human health and wellbeing, more research is crucial on electric lighting and its effect on indoor microbiology. This study aims to begin investigating this concern and provide a general overview on electric lighting's role on indoor microbiomes and give a basis on which to conduct further experiments regarding the topic.

Core Hypotheses

- Electric LED light with a high level of blue wavelengths will reduce the survivability of E. coli bacteria colonies.
- Electric LED light will not be as effective as typical daylight on a clear day at reducing the growth of E. coli bacteria colonies.

METHODS

The first part of the study took place at Scott Edwards Architecture's office. Their office had a variety of different lighting conditions ranging from fully lit by artificial electric lighting to mostly lit by natural daylight. The research team took a tour of the office to better understand the different uses of the spaces and the necessary level of light to perform certain tasks before beginning research.

Bacteria Locations

After the tour, the research team identified six different locations (Fig. 1) throughout the office that would explore microbial growth in a variety of different lighting conditions.



Figure 1: Existing building floor plan of Scott Edwards Architecture with bacteria locations marked.

Location A is a conference room on the main floor that receives a large amount of daylight from the front windows, but additionally electric lighting can be used to further illuminate the space. This space is frequently used for meetings. Location B is an employee desk located close to the front of the office, and still receives a large amount of daylight, but is supplemented by electric lighting. This space is almost always occupied by at least one employee throughout the day. Location C is the break room that has one interior window to the main studio. This space is almost entirely lit by electric light and is only periodically occupied throughout the day.

Location D is an unoccupied desk that is further back in the studio. This space receives some daylight from the front of the office but is mostly lit with electric lighting.

Locations E and F are down in the basement studio. Half of the basement studio receives daylight from the atrium in the middle of the main studio. Location E is a conference room with no windows or access to daylight. This space is infrequently used for meetings and is larger than the conference room in the front of the office. Location F is in the back of the basement studio where there are no windows, but the space is open to the part of the basement studio that receives daylight from the atrium. Before conducting any research for the study, a Building Owner Release form was signed by Scott Edwards Architecture.

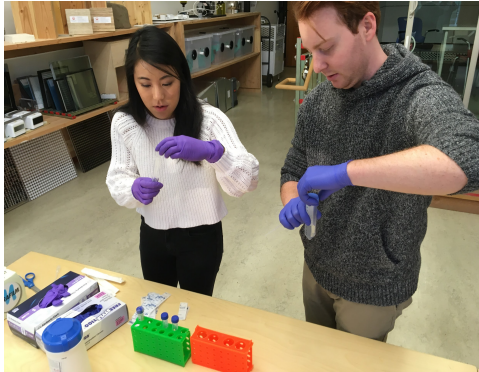


Figure 2: Making the 1:1000 E.coli concentrated solution.



Figure 3: Petri dishes and trays being labeled with the location specific nomenclature.



Figure 4: Piping the 1:1000 E.coli concentration onto the petri dishes.

Experiment 1

The research team used 36 100mm petri dishes prepared with a sterile nutrient broth agar. Then, using *Escherichia Coli* (*E. coli*) biosafety level 1 and sterile pipettes, the cells were diluted in a series of phosphate buffered saline (PBS) to a 1:1000 concentration. Next, one milliliter of the *E. coli* dilution series was piped onto the petri dishes and sealed for transportation.

The *E. coli* was stored in a refrigerator for four days, and then the morning of bacteria placement was piped onto the nutrient broth agar and distributed to their designated locations. First, the *E. coli* bacteria was mixed with phosphate buffered saline (PBS) to create a 1:1000 dilution series (Fig. 2). The research team started by using a sterile pipette to fill a sterile test tube with one milliliter of *E. coli* and nine milliliters of PBS to create a 1:10 solution. During this step the research team made sure to keep separate pipettes for each dilution series and the PBS. Next, they repeated the first step filled a second sterile test tube with one milliliter of the 1:10 solution and nine milliliters of water to create a 1:100 solution. Then, repeating the first step once more with the 1:100 solution they created a 1:1000 diluted solution.

The research team labeled each petri dish according to its designated location (Fig. 3). The nomenclature used was a letter indicating the location of the bacteria, a number representing the trial, and the letter “L” or “D” distinguishing the difference between trials and control trials (i.e. A2D). They used this same nomenclature to label the trays, as well.

Next, using the 1:1000 solution, the research team piped half a milliliter of solution onto the agar in the petri dishes (Fig. 4). They made sure to evenly coat the entire surface of the agar in order to avoid clustering of bacteria colonies. Once the *E. coli* was piped onto the agar, the petri dishes were closed and sealed with parafilm tape to ensure that the *E. coli* were only exposed to the agar (Fig. 5).

E. coli was used in this experiment because it is easy to culture and grow and it is found in the human gut. This makes it more susceptible to daylight in comparison to bacteria that have evolved outdoors. Although, the *E. coli* used in this experiment were BSL 1, they are being used as a proxy for other bacteria that are similar to human pathogens. There are certain bacteria that grow faster when in direct daylight called photosynthetic bacteria. While other bacteria have the complete opposite reaction, when exposed to daylight their growth will be inhibited. *E. coli* is not photosynthetic bacteria.

This means that the bacteria will die if they are exposed to the sun. A study looking at the survival of *E. coli* in marine soils found that there was not only a dependence on environmental factors, but also a change to its adaptation capacity (Anuar 2016).

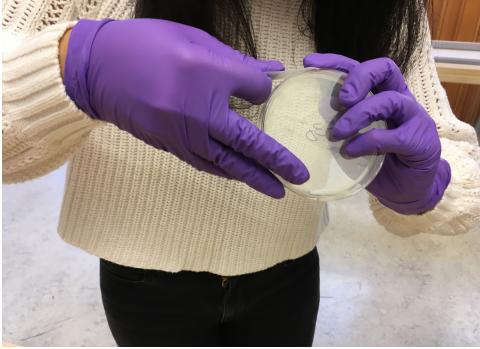


Figure 5: Petri dish being sealed with parafilm wax tape.

Once the bacteria locations were determined and the petri dishes were prepared, the research team designed the process for measuring bacteria growth. Each location had six petri dishes (Fig. 6). Three were exposed to the location's lighting condition, and the other three were covered with a black box. The covered petri dishes were used as a control for the experiment. Next, the research team programmed the data loggers to measure temperature, relative humidity and light intensity. Each data logger was set to start collecting data at 8:00am the day of bacteria placement at five-minute intervals. This was to ensure that data collection captured the entire time the bacteria were at their designated locations. Then, they assembled the tray with the petri dishes and data loggers at each location.



Figure 6: Tray at each location with three trial petri dishes, 3 control petri dishes covered by a black box, and a hobo data logger.

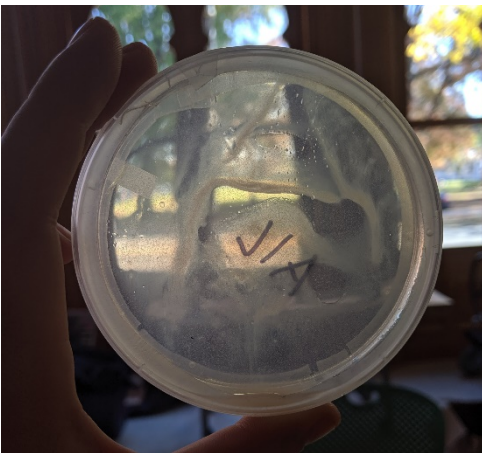


Figure 7: Film of bacteria that had grown on trial one of location A in the mostly daylight conference room.

The tray design was used to keep a consistent placement of petri dishes relative to the data logger at each location. Additionally, the trays allowed the researchers to standardize the data collection process labelling each petri dish and each petri dish spot on the tray. Then, they created black boxes to cover the control dishes.

With the bacteria plated and ready for placement, the research team went to Scott Edwards firm and assembled the trays. The time of placement was documented for each location to be able to accurately analyze the data logger readings later.

The bacteria were left in the office for a day, and then checked to determine if growth levels were adequate for analysis. No growth was noticeable at this time, and the bacteria were left in the office for another day. There was still no growth reported on the second day, but on the third day the bacteria had grown into a thin film (Fig. 7). The bacteria film was not analyzable

by the research team, since it was impossible to count the different bacteria with the human eye. No growth was recorded on days one and two, so the research team decided to modify the experiment and test the bacteria again.

Experiment 2

The second part of the study took place at the University of Oregon's Energy Studies in Buildings Laboratory. In a laboratory setting, the E. coli bacteria were piped onto petri dishes prepared with nutrient broth agar and exposed to daylight and three other LED lighting conditions (Fig. 8).



Figure 8: The experiment setting with daylight trial and three separate lighting trials.



Figure 9: Measuring the spectral light intensity in each light box.

A new nomenclature was for the lab-controlled experiment starting with letters "DL" or "EL" representing daylight or electric LED light, then a number indicating which lighting condition the trial received, and last a letter identifying trials from controls (i.e. EL1.2C). The remaining E. coli bacteria had been stored in the refrigerator for two weeks were used in the second experiment. Following the same process as the first experiment a dilution series was used to create an E. coli bacteria solution with the concentration 1:1,000,000. Once the diluted E. coli solution was created, half a milliliter was piped onto each petri dish. The research team used 24 100mm petri dishes prepared with nutrient broth agar.

During the experiment, six petri dishes and a hobo data logger were placed in each condition. The hobo data logger measured the light intensity, relative humidity and temperature of each condition. Three petri dishes were exposed to the lighting condition, while the others were covered with a black box as a control. For each of the lighting conditions a black cover was placed on the back of the box to ensure that the bacteria were only exposed to the light in the box.

Next, the research team set the light intensity of each box to relatively 1920 lux. Then, they took spectral light readings using a Konica Minolta CL-500A Spectrophotometer of each light box and a static measurement of the daylight at the end of the experiment. These readings showed the light spectrum and intensity in each box and the daylight at the end of the experiment (Fig. 9). After exposing the bacteria to their designated lighting conditions for two days, they were placed in incubation chamber for two days to grow. Lastly, the research team counted with the human eye the bacteria colonies that were present.

After the research team visited Scott Edwards Architecture to measure the spectral lighting intensity in the spaces that were tested in their office. This data was compared to the results from the light boxes that most closely match the lighting condition.

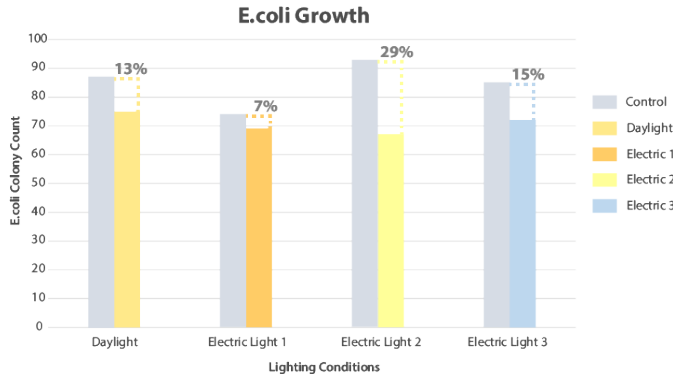


Figure 10: The reduction in viability of bacteria in the different lighting conditions compared to the control.

RESULTS

The results of the experiment showed the different effects of daylight and different LED lighting on the viability of *E.coli* growth (Fig. 10). The daylighting condition reduced the viability of the bacteria by 13% in comparison to the control. Electric Light 1 reduced the viability by 7%, Electric Light 2 reduced the viability by 29% and Electric Light 3 reduced viability by 15%.

The reduction in viability percentages were generated from the bacteria colony counts that were generated from the petri dishes after incubation (Fig. 11). The research team has changed the color of the photos of each petri dish to easily count the bacteria

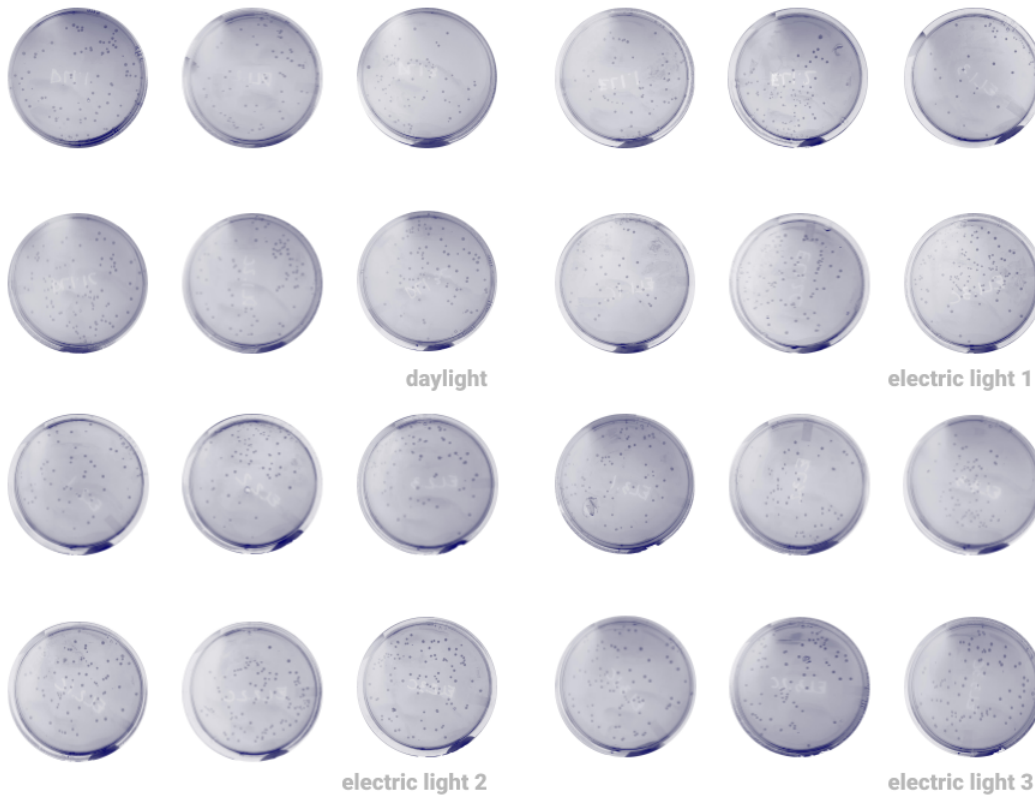


Figure 11: The photos of each petri dish and the bacteria colonies that grew.

colonies. The photos were printed out so that each colony that had been counted could be marked ensuring that all colonies were counted, but there was no double counting.

The spectral graphs below (Fig. 12) represent the intensity of different spectral wavelengths in each lighting condition. The x-axis shows the wavelength in nanometer, and the y-axis shows the spectral intensity. The wavelength of the light determines which part of the spectrum it is from. Daylight had a light spectrum with a wide range of colored wavelengths. (Fig. 13). Electric Light 1 had a light spectrum with high levels of red

wavelengths (Fig. 14). Electric Light 2 has a light spectrum with high levels of orange and blue wavelengths (Fig. 15). Electric Light 3 had high levels of blue wavelengths (Fig. 16).

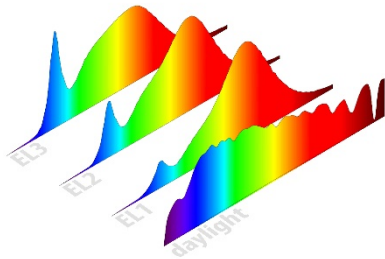


Figure 12: Spectral reading summary of all four lighting conditions.

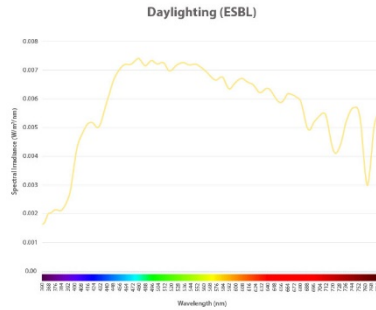


Figure 13: Static measurement of the light spectrum of daylight at the end of the experiment.

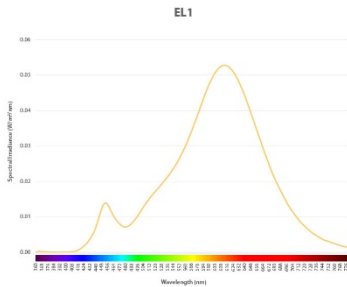


Figure 14: Electric Light Control Box No.1 measurement of the light spectrum.

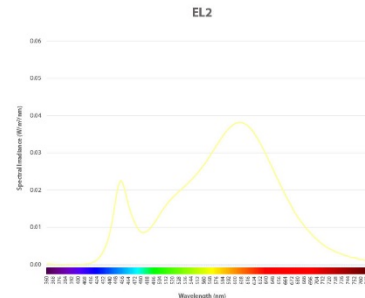


Figure 15: Electric Light Control Box No.2 measurement of the light spectrum.

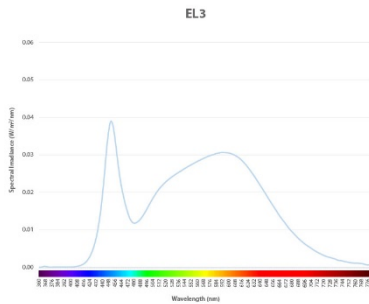


Figure 16: Electric Light Control Box No.3 measurement of the light spectrum.

Environmental Conditions

environmental conditions of each light box were similar. The temperature was almost the same in each light box (Fig. 17). The drop in temperature in middle of the experiment happens at night. Naturally daylight condition is slightly cooler and varies a lot more. The temperature of the daylight experiment lower because it was in the open air of the lab, versus light boxes that were enclosed to only expose the bacteria to the intended lighting condition.

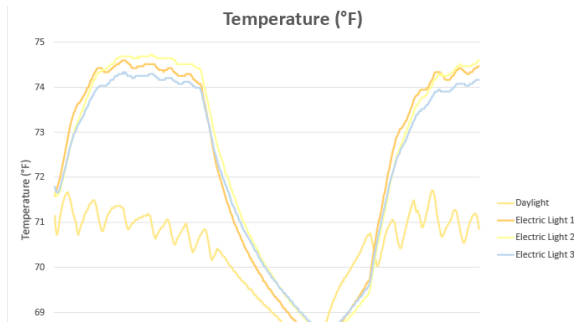


Figure 17: The temperature of each lighting condition over the two-day exposure period.

The humidity of each lighting condition was proportionally similar throughout the experiment (Fig. 18). All four of the lighting conditions saw peaks in humidity during the middle of the day, and a drop in humidity during the evening. Although, Electric Light 2 was the most humid box. The lower point of humidity was still greater than the highest point of humidity for other boxes. Electric Light 1 and 3 had very similar humidity. Lastly, daylight had the lowest humidity. This can be attributed to the open-air exposure to the lab which was a much larger space than the light boxes.

The light intensity of each lighting condition varied because of the various light spectrums (Fig. 19). At the beginning of the experiment each light box was

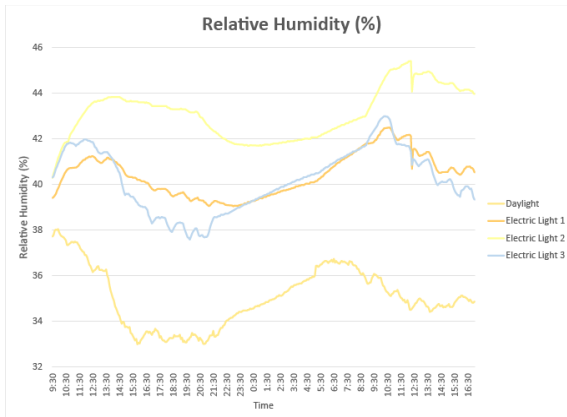


Figure 18: The relative humidity of each lighting condition over the two-day exposure period.

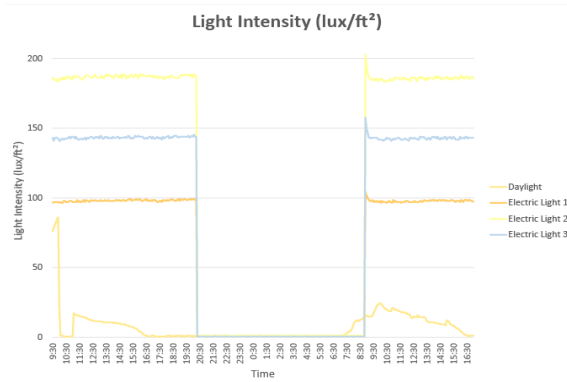


Figure 19: The light intensity of each lighting condition over the two-day exposure period.

my increase in areas closer to the equator and decrease in areas farther away from the equator. Also, in areas closer to the equator the amount of exposure to daylight is relatively consistent all year round, whereas it is more variant farther away from the equator. While the results of this experiment showed that LED lighting with high levels of orange and blue wavelengths are equally or more effective at reducing the viability of *E.coli* bacteria, these results may not be representative of results that would be found in other areas and climates.

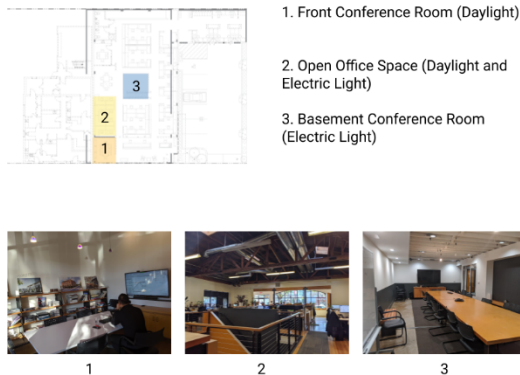


Figure 20: The three different lighting conditions included in the analysis.

set relatively to 1920 lux. Although, due to the bulb intensity and spectral variation in conditions the light intensity varies. Daylight is significantly less intense than the light boxes, and the experiment was conducted during clear days.

ANALYSIS

The results of the experiment show that electric LED lights with a high level of orange and blue wavelengths are equally or more effective at reducing the viability of *E.coli* bacteria. LED lighting with just orange and blue wavelengths may not be as effective at reducing viability looking at the light spectrum of Electric Light 2 and Electric Light 3 there are still red and purple wavelengths present, but the highest levels are in orange and blue wavelengths.

It is important to note that the overall light intensity of Electric Light 2 and Electric Light 3 are significantly more intense than daylight. While the light intensity of each light box was set to 1920 lux there is great variance in intensity due to the type of residential light bulbs and light spectrum. Furthermore, looking at the light intensity graph (Fig. 19), daylight exposure was for 14.5 hours and LED lighting exposure was for 19 hours. The variance in intensity and exposure time could suggest that daylight may be equally or more effective at reducing the viability of *E.coli* if it had the same light intensity as the light boxes and was exposed to the bacteria for the same amount of time.

Additionally, when this experiment was conducted the weather was clear in Portland, OR. Therefore, the daylight in this study does not represent all daylight everywhere. The frequency and intensity of daylight

Scott Edwards Analysis

When comparing the lab results to the different lighting conditions at Scott Edwards Architecture some spaces have similar light spectrums to others. Therefore, this analysis focuses on three lighting conditions (Fig. 20).

These three areas represent the most of the different lighting conditions through the Scott Edwards Architecture office. The front conference room lighting condition is most similar to daylight (Fig. 21) This means that this area is likely to reduce the viability of *E.coli* and other human pathogens at a rate similar to daylight.

The open office area lighting condition is most similar to Electric Light 1, which had high levels of

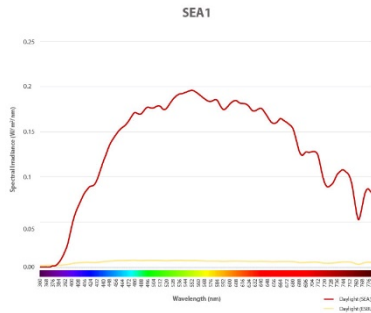


Figure 21: Front conference room lighting spectrum overlaid with the daylight lighting spectrum.

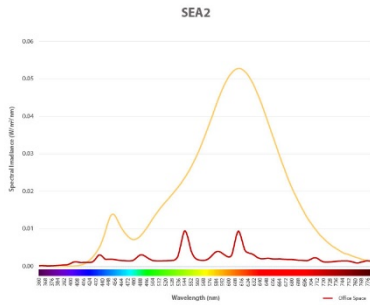


Figure 22: Open office space lighting spectrum overlaid with Electric Light 1 lighting spectrum.

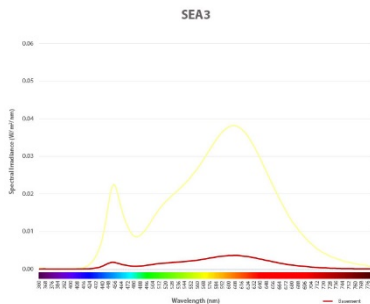


Figure 23: Basement studio space lighting spectrum overlaid with Electric Light 2 lighting spectrum.

red wavelengths (Fig. 22). The results of the experiment showed that LED lighting with high levels or red wavelengths were less effective than daylight at reducing the viability of E.coli. This suggests that the open office space at Scott Edwards Architecture may require more cleaning to adequately reduce the spread of human pathogens.

Lastly, the basement studio lighting condition is most similar to Electric Light 2, which had high levels of orange and blue wavelengths (Fig. 23). The results showed that Electric Light 2 was more effective at reducing the viability of E.coli. This suggests that the basement studio and front conference room may require the same level of cleaning to reduce the spread of human pathogens.

Although, it is important to understand how duration of exposure change the effectiveness to reduce the viability of E.coli. The basement studio may have similar lighting conditions to Electric Light 2, but in the experiment the light condition of Electric Light 2 was exposed to the E.coli 19 hours of the 48-hour experiment. If the occupancy levels vary or are less than the experiment the overall effectiveness of LED lighting may be reduced.

CONCLUSION

The results of this study added insight to the hypothesis that electric LED light with a high level of blue wavelengths will reduce the survivability of E.coli bacteria colonies. The LED lighting with high levels of blue wavelengths did reduce the viability of E.coli bacteria. Although looking at three different residential LED light spectrum, there was not one light bulb that had solely blue wavelengths. Each bulb had a combination of all the spectral wavelengths, but Electric 2 and Electric 3 had high levels of spectral intensity in the blue wavelength range. To draw any direct correlations to specifically blue wavelengths there would need to be a way to better isolate just blue wavelengths.

The prediction that electric LED light would be less effective than a typical daylight on a clear day at reducing survivability of E.coli was partially unsupported by the results. The results showed that LED spectrums that include high levels of orange and blue wavelengths were equally or more effective at reducing the viability of E.coli bacteria. While these results do not directly correlate to a reduction in the survivability of the bacteria colonies they do show more of a reduction. It is a less conclusive because there were variables about the daylight that were less controlled than the LED light boxes. The daylight was much less intense than the LED lighting, and the overall exposure to the lighting condition was less for daylight due to less hours of daylight during the day. Although the study was conducted during two clear days in Portland, OR, to confidently disprove this hypothesis more data would be needed about the light intensity levels of daylight on clear days. If the intensity does not every get any more intense than what is represented in this study the light intensity of LED lighting my need to be reduced, and the exposure time should be sync with the hours of daylight to make a more equal comparison. With the results of this study it is difficult to say whether LED lighting is more effective than daylight or it was just more exposure and intensity.

When replicating the methods of this experiment so suggested modifications would be to change the intensity of the light boxes to better match the intensity of daylight. Additionally, to keep the hours of exposure consistent between the light boxes and daylight trials. If future research were to be conducted to supplement the findings of this study, looking at specific spectral LED wavelengths would help to specifically understand the effects of different parts of the electric light spectrum. Also, looking at other types of lighting that may be common in office settings will help develop a better understand of how indoor workplace microbiomes are being altered by electric light use. As humans spend more time indoors and longer days at work the impact of electric lighting on the workspace may be a crucial part of healthy indoor air quality.

This study shows that electric light with different spectral wavelengths have varying effects on reducing the viability of E.coli bacteria colonies in indoor spaces. Additional research to understand how the different spectral wavelengths effect the survivability of E.coli in comparison to daylight is key to manually managing the microbial indoor environment. As people work longer hours and spend more time indoors thinking about an LED lighting schedule of specific spectral wavelengths may be necessary to artificially manage microbial communities to maintain the diversity that is present in outdoor environments.

ACKNOWLEDGEMENTS

The University of Oregon research team would like to express thanks to those who provided them the possibility to complete this study. Specifically, they give special appreciation to Melisse Kuhn from Scott Edwards Architecture, whose contribution in guiding the team helped generate applicable and impactful results. Furthermore, they would like to acknowledge with much gratitude their professor, Mark Fretz, who advised their research and assisted with modification to the study. Additionally, Jason Stenson's assistance with data collection was much appreciated.

REFERENCES

- Anuar, N., Chan, C., 2016. *TOLERANCE OF ESCHERICHIA COLI IN DREDGED MARINE SOILS UNDER ARTIFICIAL SOLAR EXPOSURES*. Asian Research Publishing Network.
- Erickson, B., 2018. *The Allure of Healing Nature: Examining the Influence of Light and Human Microbiota on Mental Health*.
- Fahimipour, A., Hartmann, E., Siemens, A., Kline, J., Levin, D., Wilson, H., Betancourt-Roman, C., Brown, GZ., Fretz, M., Northcutt, D., Siemens, K., Huttenhower, C., Green, J., Van Den Wymelenberg, K., 2005. *Daylight exposure modulates bacterial communities associated with household dust*. BioMed Central.
- Thaiss, C., Zeevi, D., Levy, M., Segal, E., Elinav, E., 2015. *A day in the life of the meta-organism: diurnal rhythms of the intestinal microbiome and its host*. Taylor & Francis Online.
- Ursell, L., Metcalf, J., Wegener Parfrey, L., Knight, R., 2012. *Defining the human microbiome*. Oxford University Press
- Zhi, R., Yang, A., Zhang, G., Zhu, Y., Meng, F., Li, X., 2019. *Effects of light-dark cycles on photosynthetic bacteria wastewater treatment and valuable substances production*. ScienceDirect.
- Zhou, Q., Zhang, P., Zhang, G., 2015. *Biomass and pigments production in photosynthetic bacteria wastewater treatment: Effects of light sources*. ScienceDirect.