

Sugar Kelp Respiration Rates & Implications for Post-Harvest Handling

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Executive Summary

Over the course of two growing seasons, GreenWave undertook a project as part of a USDA FMPP grant to understand sugar kelp's respiration rates and its implications for post-harvest handling. To design and execute the studies, GreenWave partnered with QFresh Lab for these studies. Qfresh Lab is an independent quality, analytical, and packaging laboratory that supports fresh food industries in quantifying the physiological properties of fresh foods from fish to seaweeds to fruit/veg/fresh cut and leafy greens. Qfresh Lab also specializes in package design and modified atmosphere packaging. The project comprised two studies:

- Respiration rate studies of fresh sugar kelp at various stages of maturity throughout the growing season
- A shelf-life study to evaluate storage conditions and residual gas levels that are conducive to transporting and storing fresh seaweed post-harvest.

These studies revealed that the post-harvest physiology of sugar kelp is surprisingly similar to that of land-based plants, in that it switches from photosynthesis to respiration after it is cut from the holdfast, and that the respiration rate changes with time and temperature abuse. These findings have implications for post-harvest handling of sugar kelp because most storage containers currently used in the field are large-volume and/or airtight; based on the findings described here, such containers would be expected to exhibit quality degradation starting from the center of the container due to heat build-up and residual oxygen levels that are too low. While the use of smaller, vented containers would have a different set of operational challenges, farmers producing smaller volumes or targeting the retail/foodservice markets may wish to consider them to achieve higher product quality over longer periods of time.

About GreenWave

GreenWave works to replicate and scale regenerative ocean farming to create a new, blue economy — built and led by ocean farmers — that ensures we all make a living on a living planet. GreenWave partners with fishermen, Indigenous groups, and other under-resourced coastal communities directly affected by climate change to ensure they benefit from the industry's growth. GreenWave's vision for the industry includes resilient regional networks of small- and medium-scale farms dotting our coastlines. In these regional "Regenerative Reefs", ocean farms

grow in tandem with land-based hatcheries and processing infrastructure, scaling in sync with entrepreneurs developing and marketing value-added products. In order to drive this growth, GreenWave's Market Development Program works across the supply chain with hatchery technicians, farmers, processors, and buyers to identify barriers to growth, develop solutions, and disseminate best practices back to the field.

Introduction

New England and Alaska have seen rapid expansion of the number of people interested in and actively growing *Saccharina latissima*, a native brown macroalgae commonly known as sugar kelp. While there has been and continues to be a large amount of research on how to reproduce and cultivate sugar kelp in its marine habitat, there has been less attention paid to how to handle sugar kelp post-harvest. This has resulted in hundreds of thousands of pounds of lost crop due to mishandling.

In 2020, GreenWave received a USDA FMPP grant to support *Strengthening Market Connections for Kelp Farmers in Southern New England*. One component of this project was developing a better understanding of the post-harvest metabolism of sugar kelp, and its implications for storage and fresh packaging. The data set gathered during the initial research period in the spring of 2021 was too small to publish on its own, but was compelling enough that GreenWave self-funded another, more robust round of studies in the spring of 2022. The combined results of these two years of experiments are described in this paper.

Like many raw agricultural commodities, the hours immediately following harvest are critical for maintaining product quality throughout the rest of the downstream supply chain. However, the vertical integration of supply chains has led to a dearth of publicly available information regarding post-harvest handling best practices, because private businesses often consider their processing procedures trade secrets. This informational vacuum is compounded by lack of detailed food safety guidance from federal and state regulators.

As such, the goal of this document is to share the results of publicly-funded respiration rate studies with sugar kelp farmers, processors, and consumer packaged goods companies, and discuss the potential implications for improving the storage and packaging of fresh sugar kelp. It is our hope that this commercial research will be critiqued and built upon in a collaborative manner, to support the growth of the entire domestic sugar kelp industry.

Key Concepts

Quality

An underlying assumption of the studies described herein is that there are measurable standards that define “quality” for sugar kelp. While the industry has yet to arrive at a mutually agreed-upon set of standards, most large purchasers of sugar kelp have developed internal quality guidelines which they use to sort and grade seaweed, some of which are tied to different pricing tiers.

For the purpose of this study, we interpreted the following changes as indication of deterioration:

- Color: lighter or darker brown, changing to green
- Surface moisture: matte vs. shiny, slippery vs. tacky
- Surface appearance: bubbling, white residue, mold
- Surface texture: rubbery, brittle, mushy
- Odor: Odorless, briney, vegetal, acidic, stinking like tidal flats
- Temperature: Heat generation
- Sound: bubbling

Going forward, GreenWave plans to work with industry stakeholders to define which of these markers are most critical to end product quality, and how each can be managed in a post-harvest handling setting.

Respiration Rate

When we buy fresh fruits and vegetables from the farmers market or grocery store, we have an implicit understanding that they are in some way still alive – even though they are no longer attached to the plant. If we keep these products around long enough, though, they eventually begin to senesce, decay and die.

In the period of time between when produce is harvested and its eventual cellular breakdown and death, metabolic reactions are still happening. Specifically, tissues that once performed photosynthesis – using sunlight to synthesize nutrients and oxygen from carbon dioxide and water – switch to a function called respiration. Respiration is the same activity that humans and all other animals perform day in and day out: also known as breathing! In respiration, glucose (sugar) is combined with oxygen and transformed into carbon dioxide, water, and energy (heat).

Respiration ends, and an organism dies, when all the glucose contained in its tissues has been used up. It’s impossible to increase glucose in an organism that’s no longer performing photosynthesis, so the only thing you can do is control the speed (rate) of respiration. The

slower respiration happens, the more time you have before all the glucose is consumed (amongst other factors).

So when it comes to extending food quality, we want to keep respiration rates as low as possible *without killing the product*. We do this by controlling access to the other ingredient in respiration – oxygen.

Each organism has its own respiration rate, which can vary based on environmental and bio-physical characteristics. By studying sugar kelp's respiration rate under carefully controlled settings, we can begin to understand what types of storage containers and conditions might best preserve the quality of freshly-harvested crops.

Shelf Life

Shelf life is the length of time during which a product remains desirable. In direct shelf-life testing, products are stored under conditions similar to those that they will actually face, and monitored over regular intervals for signs of deterioration.

A product's stated shelf life is *not* a guarantee, but rather a statement of high likelihood that a product will remain usable for that time under typical supply chain conditions. A product's expected shelf life has implications for upstream supply chain logistics. For example, if a product's total shelf life is 14 days and a given retailer requires a shelf life of 10 days minimum, that product needs to be received by the retailer within 4 days of production.

Shelf life is not the same thing as food safety, though the two concepts are related. A product that has gone beyond its expected shelf life is likely not in an optimal state of quality, but it may still be physically safe to consume. If the handling of a product has violated food safety best practices, it is not physically safe to consume regardless of whether or not it is within the stated shelf life.

Methods

Respiration Rate Studies

In the springs of 2021 and 2022, GreenWave ran a series of respiration rate studies in collaboration with QFresh Lab, an independent quality, analytical, and packaging laboratory that supports the fresh produce industry in quantifying the physiological properties of fruits and vegetables. The respiration rate and shelf life tests were designed by [QFresh Lab](#) and implemented by their strategic partner, [Eurofins Microbiology Laboratory](#), in North Kingstown, RI. This location was chosen so that the seaweed did not require shipping, preserving the cold chain and improving handling.

The timing of the studies were as follows:

- 2021 Harvest Season: March 24, May 24
- 2022 Harvest Season: March 8, March 23, April 4, April 21, May 2, May 17, June 2 (approximately every 2 weeks)

In each study, sugar kelp was harvested from the GreenWave-operated Thimble Island Ocean Farm in Branford, CT and was put immediately into a mesh bag and onto a cooler filled with ice to keep it cool and moist. The kelp was separated from the ice from a protective plastic barrier.

After receiving the kelp samples, Eurofins placed the kelp into respiration rate test bags and held them at 40°F, taking daily measurements of oxygen and carbon dioxide gases, as well as organoleptic observations (i.e., how the kelp looked and smelled). The temperature 40°F was selected both because this is the current industry standard for holding seafood, and because it hedges the gap between typical storage temperatures for produce (34-38°F) and typical “abuse” conditions for produce (42-45°F).

Storage Study

In the spring of 2022, GreenWave ran an additional study with QFresh Lab in an attempt to discern how the vessel that seaweed is stored in immediately after harvest impacts the shelf life of that seaweed after 7 days of storage under refrigeration.

In this study, farmed sugar kelp was harvested from the East River of New York into one of two types of containers:

1. Half-height [MACX vented bins](#) measuring approximately 40”W x 48”L x 18”H (3ea)
2. [55-gallon poly drums](#) with lids (3ea)

The lids of the 55-gallon poly drums were fitted with septums to allow for air samples to be taken via needle from the otherwise airtight container. The drums were filled and sealed on the boat at the time of harvest, along with three (3) [USB temperature loggers](#): one in the bottom of the barrel, one in the middle of the seaweed biomass, and one at the top.

Kelp was transported without refrigeration to New Haven, CT, a process that took approximately 4 hours total at an ambient air temperature of approximately 64°F. Upon arrival in New Haven, CT, kelp was also transferred into a third type of container along with two temperature loggers:

3. [Vented produce lug](#) measuring approximately 24W” x 16” x 9”H (3ea)

All storage containers were placed into a 40°F walk-in refrigerator and monitored for one week. The sealed barrels were tested with a [Felix-950 Three Gas Analyzer](#) for O₂ and CO₂ levels, and only opened for visual inspection on Day 7. The two styles of vented bins were monitored for visual and odor indications of decay only. All bins were equipped with 2-3 temperature loggers in varying locations, which took temperature readings once every 5 minutes. At the end of 7 days,

samples from each type of container were taken to Eurofins Microbiological Laboratory in North Kingstown, RI for a shelf life study.

Results

Respiration Rate Studies

Respiration rates varied slightly throughout the course of the growing season and between testing years, but overall results stayed in a relatively narrow respiration rate band and did not appear to be significantly affected by varying ocean temperature and maturity of the seaweed at the time of harvest. This has positive implications for handling and package design. Sugar kelp performed comparably to leafy greens in shelf life tests under optimal conditions, holding its visual appearance without off-odors up until 12-18 days post-packaging.

We also found that respiration rates are impacted by the amount of time, temperature, and physical abuse sugar kelp is subjected to prior to packaging, with more time and abuse resulting in higher respiration rates. This behavior is similarly observed in leafy greens.

The complete results of the studies, including photos, can be found here:

- [QFresh Respiration Rate Report - April 2021](#)
- [QFresh Respiration Rate & Packaging Report - June 2021](#)
- [QFresh Respiration Rate Report - July 2022](#)

Storage Study

While none of the sealed poly drums reached fully anaerobic conditions within the 7 days, residual O₂ dropped rapidly to around 3.7-6.7%. However, it is likely that readings were inaccurate starting around Day 3-4, when high volatile organic carbon (VOC) readings began to interfere with the O₂ and CO₂ readings. Qfresh Lab has since ordered equipment to remove VOCs to be able to measure this accurately for future testing.

While the vented storage containers cooled relatively quickly (~28-30 hours), the poly drums were unable to do so. One of the barrels never reached below 43°F, even when stored below 40°F for 7 days. Across the board, temperature loggers in the center of the containers logged higher temperatures than those at the top, bottom, or edges of a container; this was true even of the vented containers, albeit the differential was much smaller (2.2°F vs. 10+°F. Both the barrels and the MACX bins showed a temperature spike immediately post-packing, while the small vented produce totes did not. The bulk density of the product, combined with the respiration rate of the product, held more heat than the vented totes.

The smaller vented produce totes performed better from a visual and odor perspective than the larger MACX bins. However, in both cases the kelp on the top of the bins showed significant dehydration relative to the kelp in the middle of the bins.

It was not possible to discern any shelf life differences between the 3 types of storage containers, as significant deterioration had already occurred prior to transporting the seaweed to Eurofins. But what was clear was the heat was able to be pulled out of the product with smaller containers, and sealing the kelp has the potential to reach anaerobic conditions quickly.

The complete results of the studies, including photos, can be found here:

- [QFresh Storage Testing Report - June 2022](#)

Discussion

What we learned

First and foremost, we learned that the post-harvest physiology of sugar kelp is similar to that of land-based plants, in that it switches from photosynthesis to respiration after it is cut from the holdfast. This was not necessarily a given, since plants and algae are fundamentally different organisms. The implication of this is that similar to fresh-cut produce, sugar kelp will not begin to degrade immediately as long as it is kept cool, moist, *and has access to oxygen* allowing it to respire. In addition, we learned that modifying the atmosphere in the package extends the shelf-life of kelp, similar to most fruits/vegetables.

Second, we learned that there is a difference in respiration rate based on when atmospheric conditions are controlled relative to harvest. The longer you wait to protect kelp from heat and dry air, bring the temperature down, and control the ambient levels of oxygen and carbon dioxide, the higher the respiration rate will be and the more product degradation will result. While respiration rate is not a 1:1 correlation to shelf-life, it does give an insight into the robustness of the kelp. The data captured in these studies provide a solid baseline to compare future results against.

We learned that, on average, mature kelp has a shorter shelf life than juvenile kelp — in our very limited testing, we observed a shelf life of 9 days for mature kelp versus up to 16 days for juvenile kelp. A host of factors are at play in shelf life, and further testing is required to validate these results. If kelp continues to follow similar trends to leafy greens, there will be a range of maturity that is optimal, and overmature kelp will most likely continue to exhibit a shorter shelf life. It is still not clear whether this is purely due to the age of the tissue, or whether respiration rate differences, water temperatures, or other factors also have an impact on quality.

Implications for Post-Harvest Handling

Similar to fresh produce, sugar kelp quality is at its peak at the time of harvest. It is impossible to *improve* crop quality from there on out — the best you can hope for is to *preserve* it through proper post-harvest handling techniques. These include maintaining optimum levels of (1) temperature, (2) humidity, and (3) gasses required for respiration. If these three factors are controlled, this study suggests that sugar kelp shelf life could be up to 14 days, a period of time comparable to leafy greens. During the scope of this study, we sought to understand and to design packaging to address the third factor (residual gas in package) only; future studies will aim to determine optimal temperature and humidity levels.

By using modified atmosphere packaging (MAP), the metabolism of sugar kelp can be slowed down, reducing heat and water generation. Simply put, MAP is packaging that is designed to control the transmission of gases such that the atmosphere inside of a package is altered from that of the ambient air, through the use of specialized materials and small holes (microperforations) in the materials. After the package is sealed, the atmosphere in the package will eventually reach an equilibrium point between oxygen and carbon dioxide. This equilibrium point is reached due to the respiration rate of the product in concert with the package design transmission rate. The lower oxygen levels slow down respiration and other cellular processes, and the increased carbon dioxide creates a slightly acidic environment, which slows down the growth of spoilage bacteria. Increased carbon dioxide also causes a negative feedback loop, slowing the respiration rate even more. MAP does not necessarily need to involve adding or removing gasses (known as active MAP), and therefore would be allowable as a farming activity rather than a processing activity under federal food safety regulations.

In order to take full advantage of the benefits of MAP, QFresh Lab recommends borrowing best practices from the leafy greens industry, including:

- Cooling fresh seaweed as soon as possible after harvest
- Dewatering seaweed after cleaning and prior to packaging
- Packaging seaweed as soon as possible after cooling, cleaning, and dewatering

Even prior to packaging for retail and wholesale sales, the results of these studies are relevant. Many ocean farmers today are using large insulated fish totes for storing and transporting kelp — totes which do not provide *any* access to oxygen other than the topmost layer of product. Other farmers use large woven brailer bags, which provide some airflow on the sides and bottom, but still deprive hundreds of pounds of kelp in the center of the bag of access to oxygen. Based on our research, kelp stored in sealed containers is at risk of using up all the available oxygen. Once anaerobic conditions occur, the kelp will begin fermenting, causing off flavors and off odors, rapidly degrading the quality of the entire load. Furthermore, large containers make it difficult if not impossible to adequately chill kelp in the center of the mass, posing a food safety and quality risk. It is likely that using smaller, vented storage vessels similar to the produce totes used in the leafy greens industry will produce better results.

Ideal storage and packaging procedures may vary depending on the age of the kelp, time of the season, and other harvest conditions (such as length of time to cool, container type, etc.). Containers must ensure oxygen stays in the optimal range, especially not reaching anaerobic conditions, regardless of these other factors. Expiration dates throughout the season may need to change to properly meet consumer expectations of quality at the end of the stated shelf life.

Based on the similarities observed between sugar kelp and other forms of produce, other factors that likely affect shelf life of sugar kelp include:

- Tissue damage
- Exposure to light
- Washing and blanching
- Ambient oxygen and carbon dioxide concentration
- Water temperatures at the time of harvest and throughout growth
- Air temperature at the time of harvest
- Tissue location (holdfast, stipe, blade, and/or location within the blade)
- Other marine and/or geographic factors

Conclusion

Based on the studies described above, sugar kelp's shelf life can be extended *if* post-harvest handling is optimized to account for the seaweed's need for oxygen after it is removed from the water. This would make it feasible as a fresh or foodservice product with a shelf life comparable to leafy greens, but it also has implications for storage and transportation of sugar kelp for other applications. Additional research is needed to determine what other factors may influence respiration rates and shelf life of sugar kelp, and how to balance access to oxygen with those other factors.

References and Resources

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