JULIO GLATT BIOMIMICRY CONSULTANCY

LEAF VENATION REPORT

Addressing Function to Form

Image 1: Fig leaf veins. Richard Ricciardi. Flickr 2013

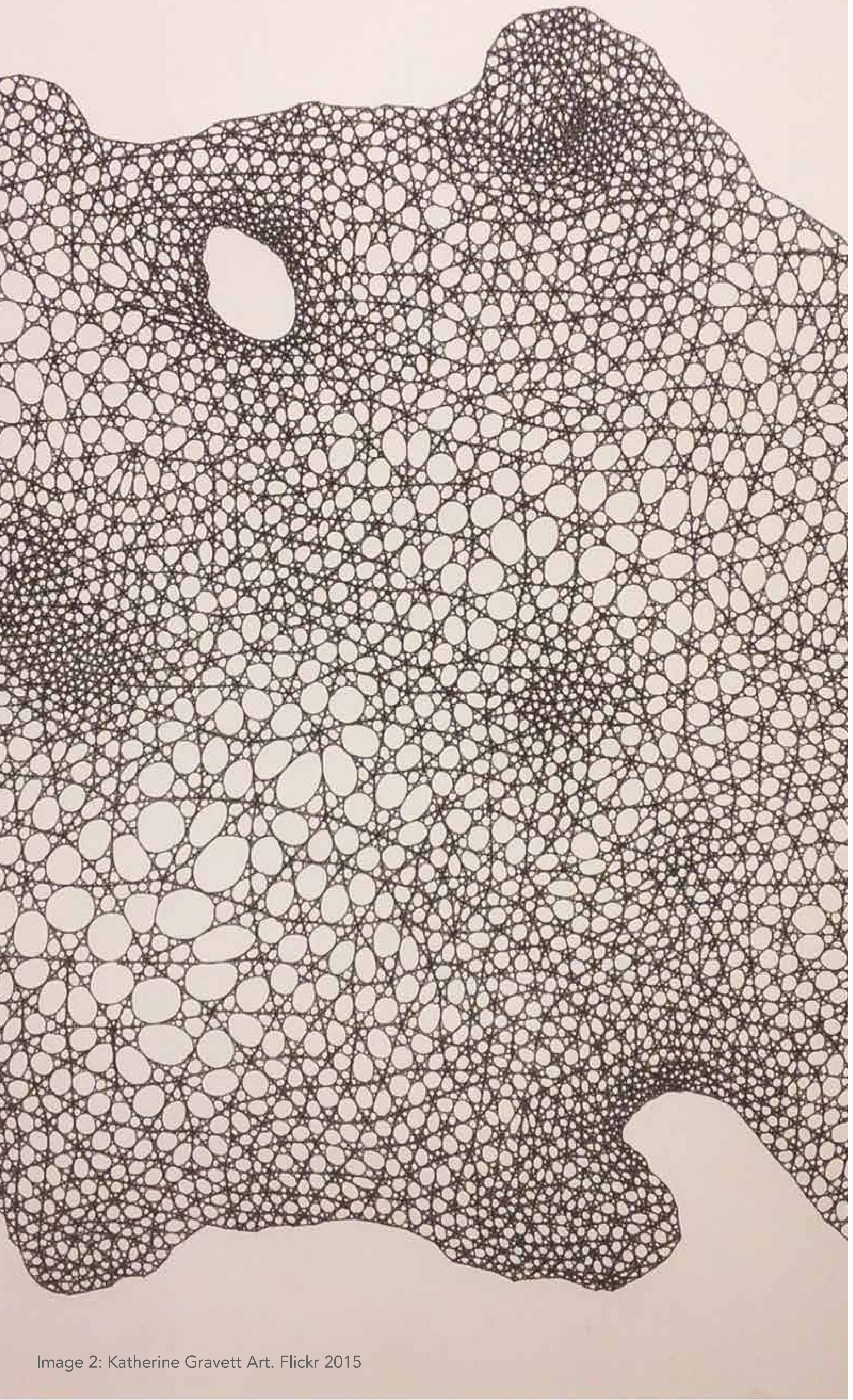


Image 2: Katherine Gravett Art. Flickr 2015

BIOMIMICRY
RESEARCH METHODOLOGY

Biomimicry is the practice of asking the natural world for design advice and emulation its designs. Life has evolved over 3.8 billion years to address many of the same problems that humans face today--gathering fresh water, harvesting energy, and even forming communications and distribution networks, to name a few. Life does this all while enriching their surroundings and providing opportunities for other organisms to thrive. By looking at natural forms, processes, and ecosystems for guidance on our human design challenges, biomimicry hopes to move humanity from a system of minimizing harm done to the environment to one where we add the same value and abundance to our surroundings that every other organism does.

LEVELS OF EMULATION

In biomimicry, it is possible to emulate the nature's genius in three different ways:

The first way is mimicking the natural form, like the shape, structure, size. For example, in this report, we will be emulating the leaf venation structure.

The second way, is deeper in complexity, it mimics the natural process, or how a thing is made, like chemistry and modular development. Yet with the leaf venation example, the intense flow of the liquids inside the veins projects the leaves toward lights, hydrate and provide physical resistance.

The third and last level is the mimicking of natural ecosystems. It means mimicking how things behave and relate with others things and its surroundings in a regenerative way. For example, the leaf shape, venation, color and position are deeply related with all the plant's survival skills, determined by the non-stoping interaction with the flora and fauna that surrounds it and by the sun, rain, drought and other abiotic factors that influence most.

If we manage to develop something that mimics the three levels of biomimicry: the form, process and system, we start to create conditions conducive to life, as nature does. To survive as humanity, we need to create conditions conducive to our own survivability, and that includes nature, since we are biological beings in the same ecosystem conditions.

Biomimicry level emulated in this report:

Natural Form

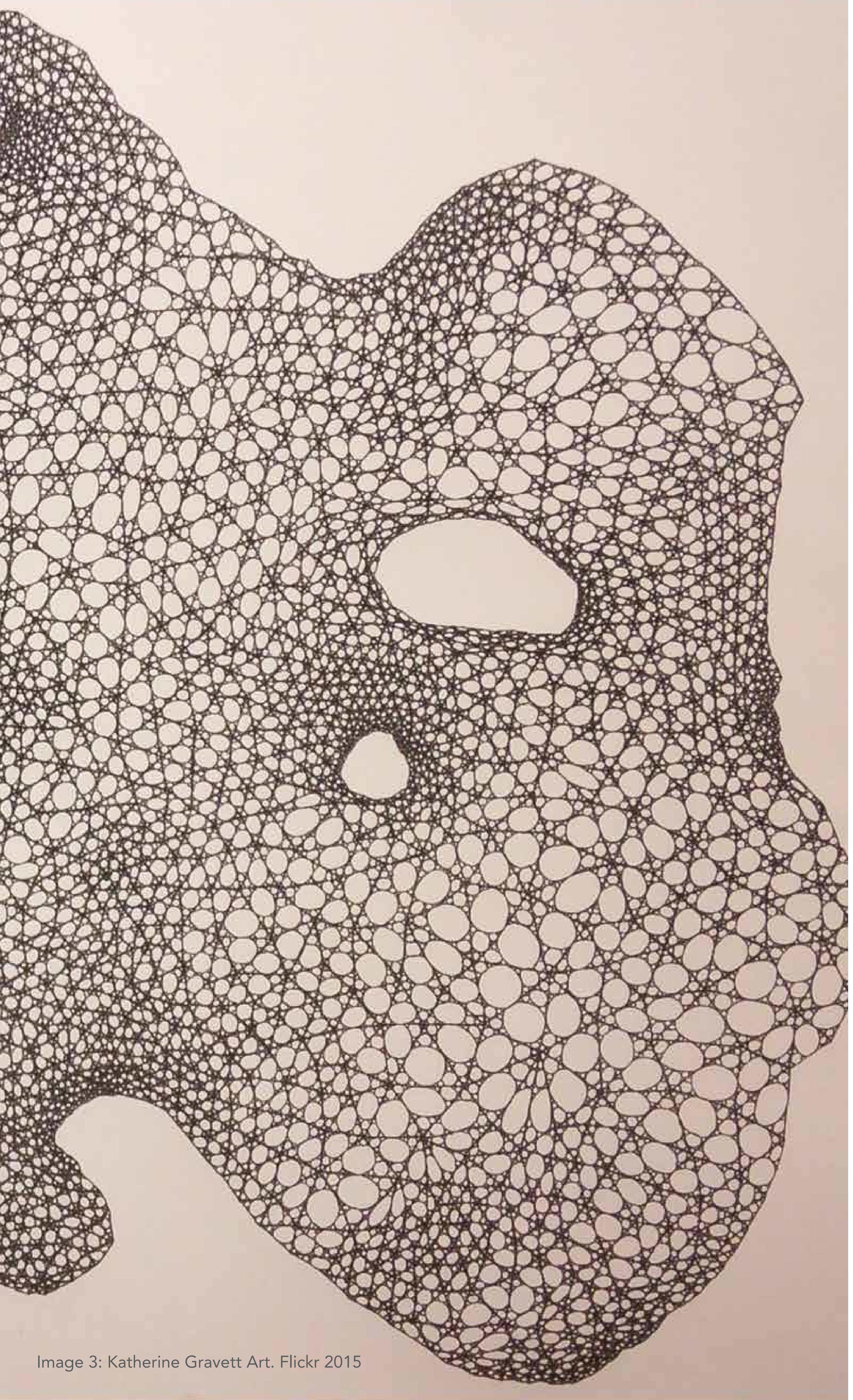
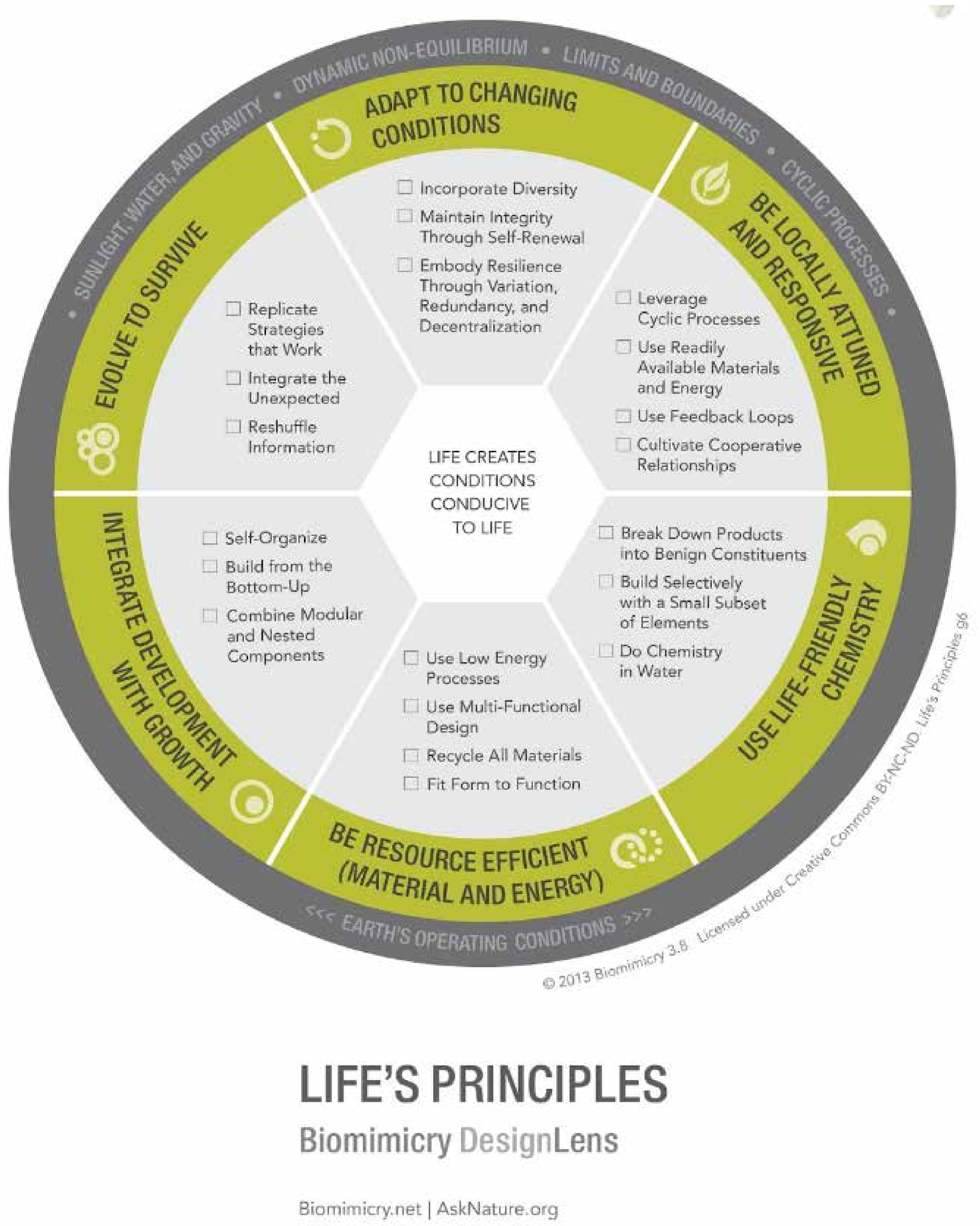


Image 3: Katherine Gravett Art. Flickr 2015

BIOMIMICRY
RESEARCH METHODOLOGY

Life’s Principles:

Life's Principles are an important component of the practice of biomimicry. As defined by Biomimicry 3.8, they are a set of deep principles or patterns that all organisms and systems on Earth meet to sustain themselves and life on earth. They are abstracted from biological literature and translated into generic design language so that they can be used by the designers of our world. When used as sustainability goals in the beginning of any design process and as a means to evaluate a design by the same measure the natural world uses, Life’s Principles can illuminate a path towards products, services, and systems that truly ‘fit in’ with our surroundings, rather than overtake them.



Explorer wants to know his destination through veins of the palm's leaf

. . . Jawahar Gupta

Image 4: Henriettea Leaf. E. P. Mallory. Flickr 2013

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OKA BIOEMBALAGENS

Image 5: Oka's products

OKA Bioembalagens is a biotechnology company in Botucatu, São Paulo, Brazil. It develops sustainable disposable products with Agricole leftovers, also develops edible, crunchy, fiber-rich and zero gluten packing and dishes.

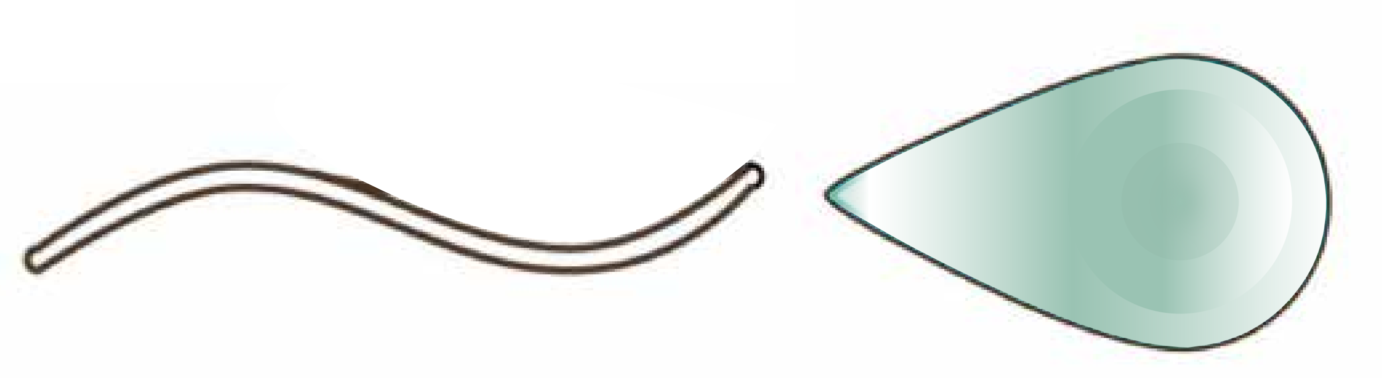
It aims its efforts to succeed in changing the Brazilian packaging industry unsustainable standards.

Clean Production,
Closed cycle,
Renewable raw material,
Natural fiber out of agribusiness waste
Ergonomic
Thermal insulation and non-toxic.
100% biodegradable.

Image 6: Cherry Leaf. Fermion. Flickr 2016 / Image 7: OKA's Products.2017

OVERVIEW
DESIGN CHALLENGE

Image 8: Sketch developed and privded by OKA



The company has a product line of disposable and edible finger food dishes (spoon, mug, plate, cup etc). Many structural studies were made to develop the adequate thickness and density of the product. The production method is water-based, uses a renewable and organic material, is made at ambient temperature and have an unharmful by-product, water vapor. Its production method respects a specific material thickness, otherwise, some parts will not harden, and other will harden too much to the point it cracks easily.

The products also follow an aesthetic concept, the mimic of natural objects. The spoon is shaped like a bent leaf, for example. The natural aesthetic given to these products are, as said before, only visual.

This research is focused only on the Leaf Shaped Spoon

Its shape is like a dry leaf bend and it also displays vein patterns (venation) that can be seen at the bottom, but they do not intentionally provide structural reinforcement or any other function besides aesthetic.

OKA wants to enhance it aesthetically and structurally by adding Leaf venation patterns to the bottom surface of its edible spoon. Their production method is already established, so, only the leaf venation pattern will be developed in with this research and applied in the 3d model.

This leaf venation structure research will be done to find a venation pattern that matches the structural reinforcement for pressure distribution that the spoon need (the point loads). They are also expecting to use less material as consequence of the structural reinforcement.

Provide to the customers a natural feeling, a biophilic sensation, so the vein pattern must not be too different from what people are used to imagine in their leaf archetypes.

All the study and venation pattern development takes into consideration the production/resource/industrial requisites and constraints that OKA has. In other words, information including size, thickness, utilized material and production methods are pre-established by the company.

The intention is to start making OKA's products become coherent with what they intend to sell and tell to customers itself and reduce material use. The leaf-shaped spoon, after this project, will be a coherent product that not only aesthetically mimics a leaf but uses one of the leaf venation patterns function and strategy: physical resistance by structural optimization.

How does leaf venation provide structural optimization?

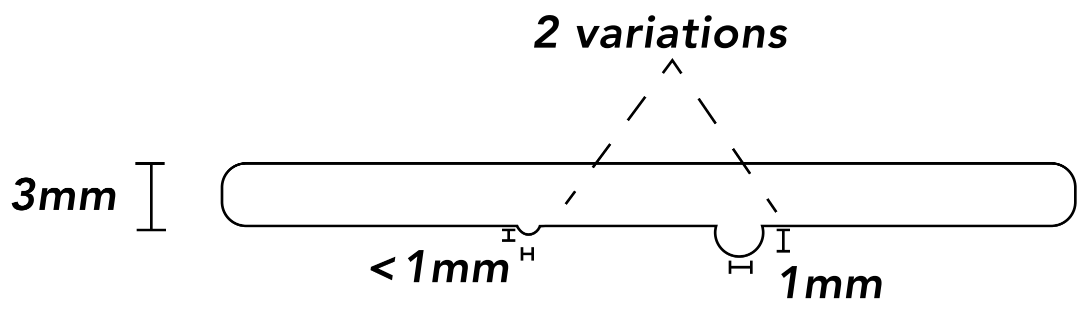
This question allows a discovering of the unique strategies and characteristics of leaf venation and dive deep to understand the mechanism

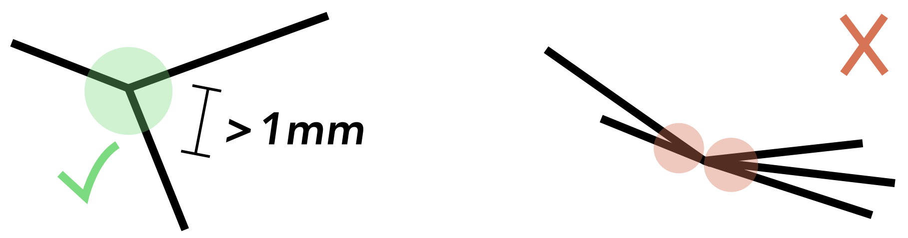
Image 9: Dried Leaves. Liz West. Flickr 2013 / Image 10: OKA's example of material prominency.

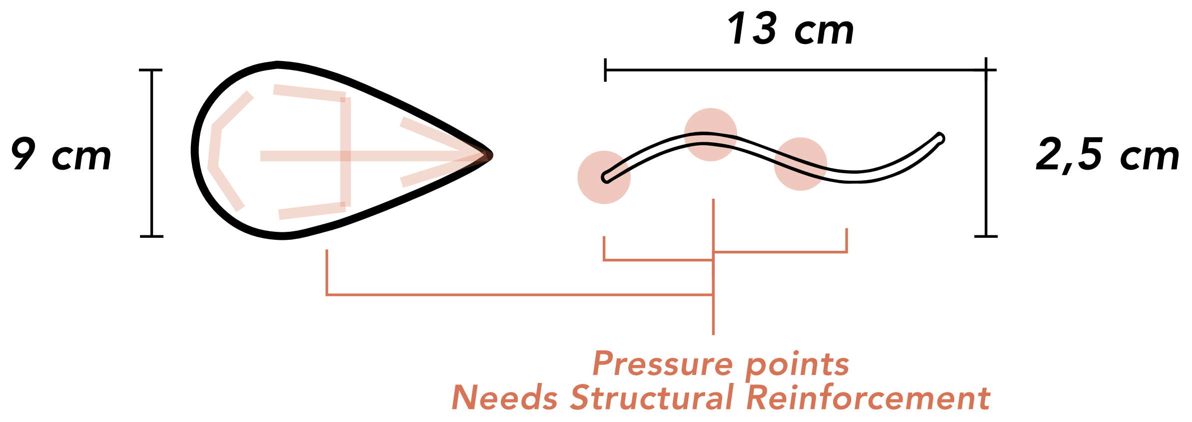
OVERVIEW

DESIGN CONTEXT

As mentioned previously, the design context consists basically in a specific and unchangeable material qualities and production method, wich means any design proposition done with the lessons learned from the leaf venation report should take this constrains in consideration.







" Structures must not make the spoon too strong. It must be breakable to anyone's bite. "

OKA Bioembalagens

Production

- *Water-based*
- *Uses a pulp-like material made from manioc starch and agricultural leftovers*
- *Does not use heat*
- *Water vapor as the by-product.*

Thickness

• The Material must respect a maximum thickness of 3 mm. Therefore, the venation patterns to be developed should have the maximum thickness and prominence height of 1 mm and should have 2 prominence height variations. Materials should dry homogeneously.

Spacing

• The spaces between the venation lines should be larger than 2 mm. If not respected, the proximity of two lines could end up gathering a more than wanted material quantity to a specific place, making it dry differently from the rest of the spoon.

Size and Pressure points

The size of the Leaf Shaped Spoon is 13 cm x 9 cm x 2,5 cm. Due to the curvature of the spoon, the parts indicated in the image have an increased load/pressure tension, these parts need structural reinforcement.

DISCOVERING – RESEARCH

LEAF VENNATION

Image 11: Miconia Leaf. E. P. Mallory. Flickr 2013

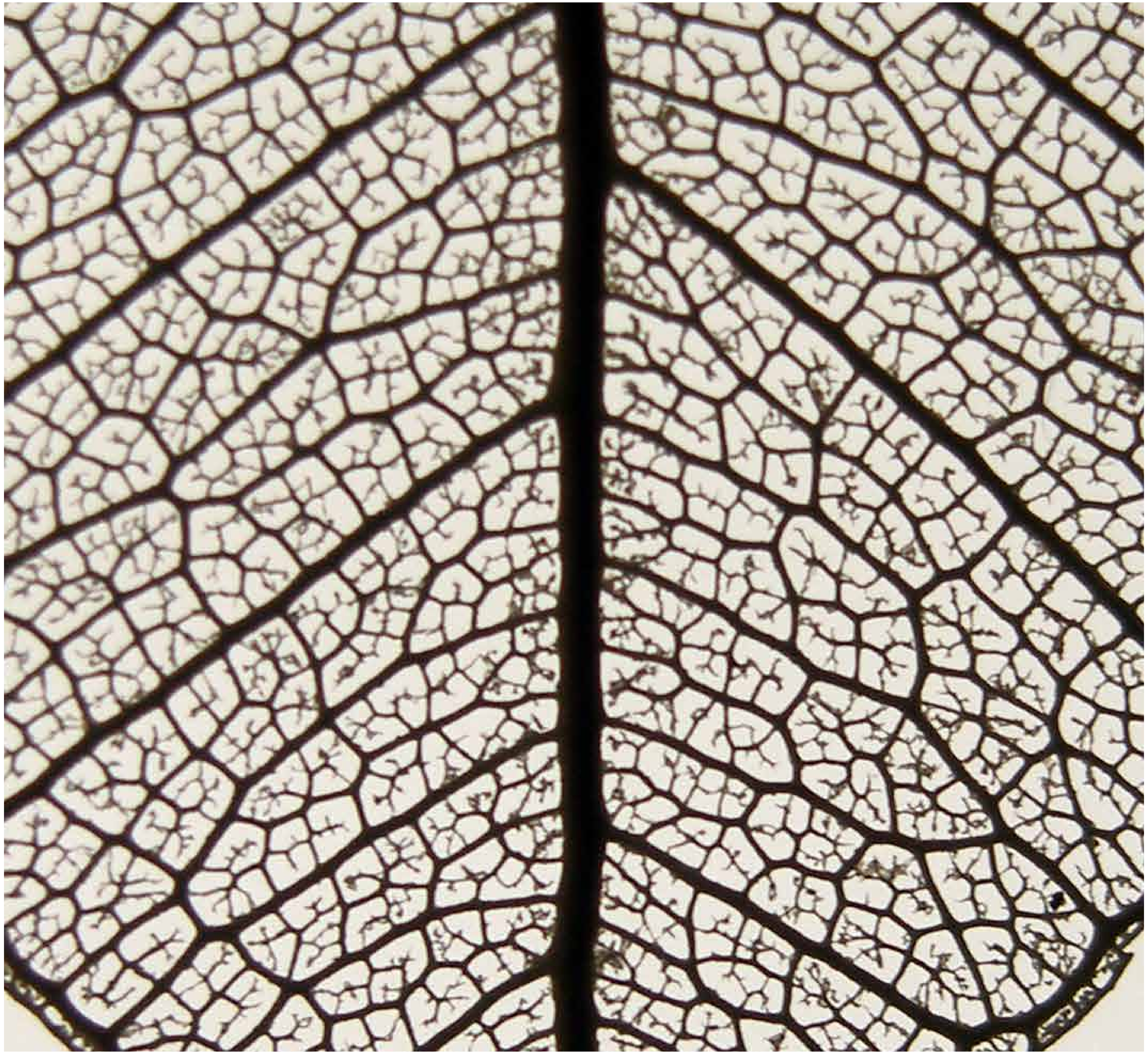


Image 12: Dry leaf venation. Sigmund Gundersen. Flickr 25

DISCOVERING

LEAF

FUNCTITON

Maintain Physical Integrity

Preventing Strucutral Failure/
Managing Strucutural Forces

STRATEGY

Optimize physical structure

MECHANISM

Leaf Venation

MECHANISM

LEAF VENATION

Leaf is the most important organ/part of a plant. It is responsible for the photosynthesis. It is a photosynthetic blade and it must have access to light. There are some structures including leaf shape, margin shape, tip, lamina, petiole and vascular system pattern (Venation) present in the leaf that helps it to have access to nutrients/water, be physically resistant, allow growth and drive themselves towards the light.

The vascular system of plants transports nutrients and water through all of it.
The vascular system present in the leaf, specifically, is called venation/leaf veins, it not only transports nutrients/water but also plays a major role in the leaf mechanical support and physical protection.
Veins size, shape, pattern and hierarchy are characteristics that differ one venation from another, functionally and aesthetically. Basically, Leaf veins connect the blade to the petiole, what connects the leaf to the stem. The main vein is also called as the midrib or primary vein, other veins than the primary vein are named accordingly to their position in the hierarchy (secondary, tertiary, and so on…).

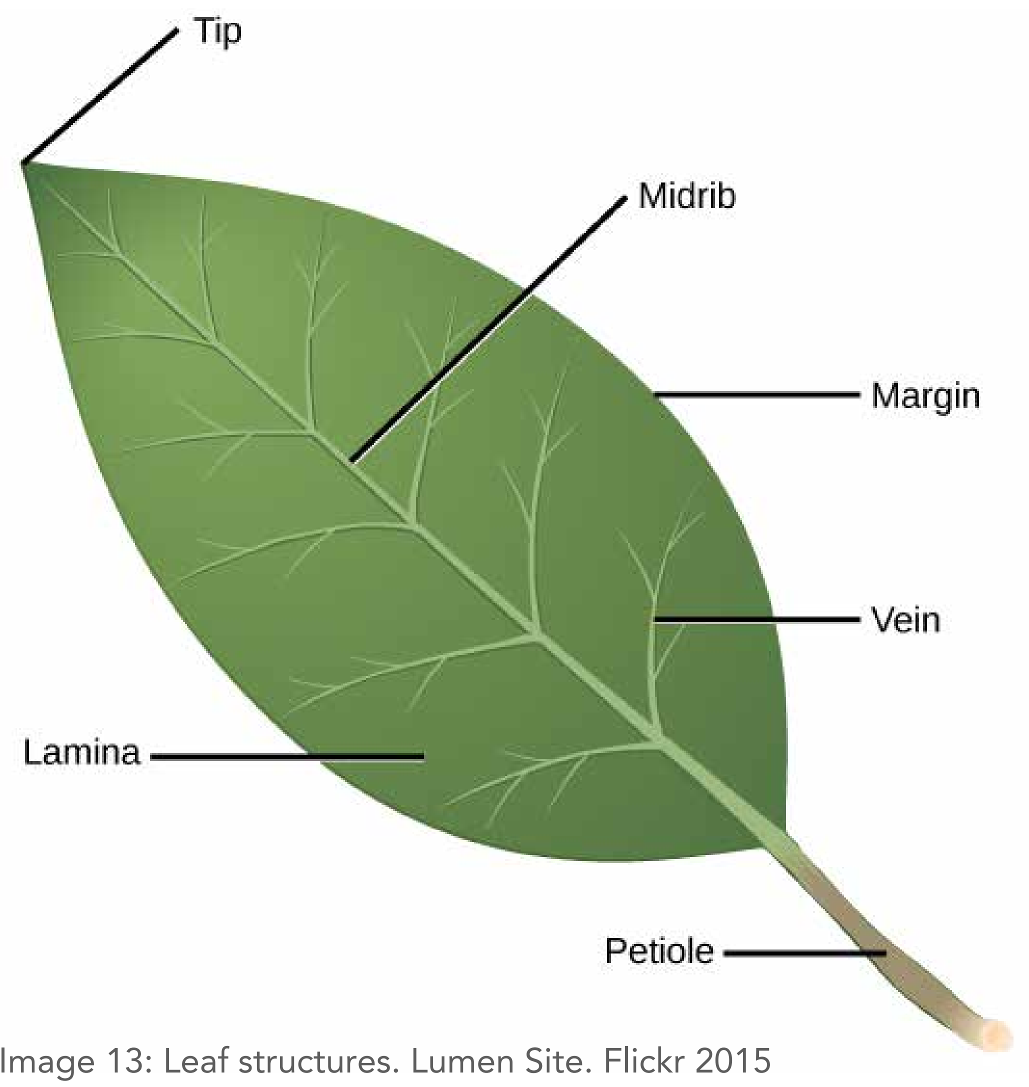


Image 13: Leaf structures. Lumen Site. Flickr 2015

These are the types of Venation.
Thicker veins represent Primary veins, smaller veins represent secondary.

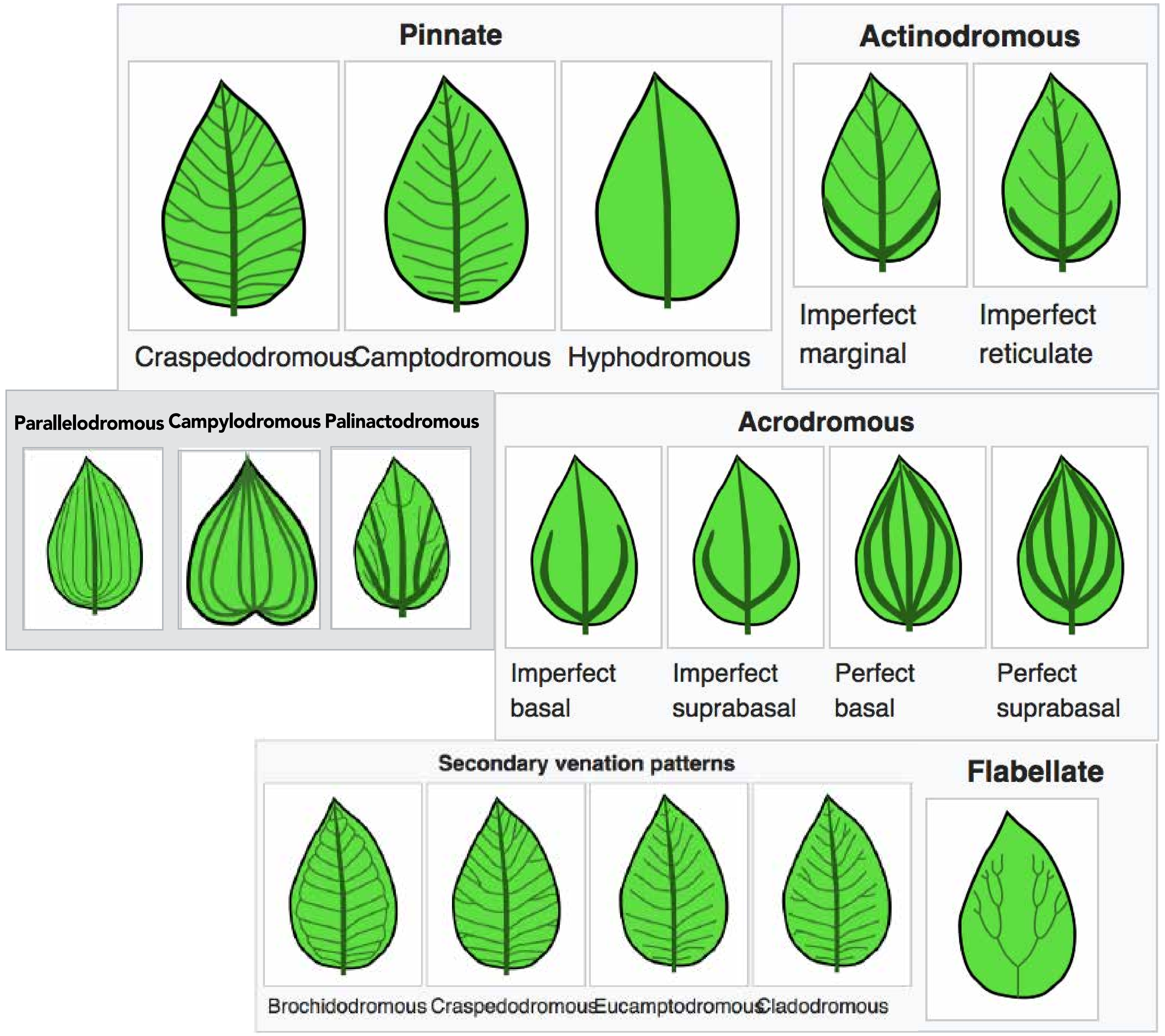
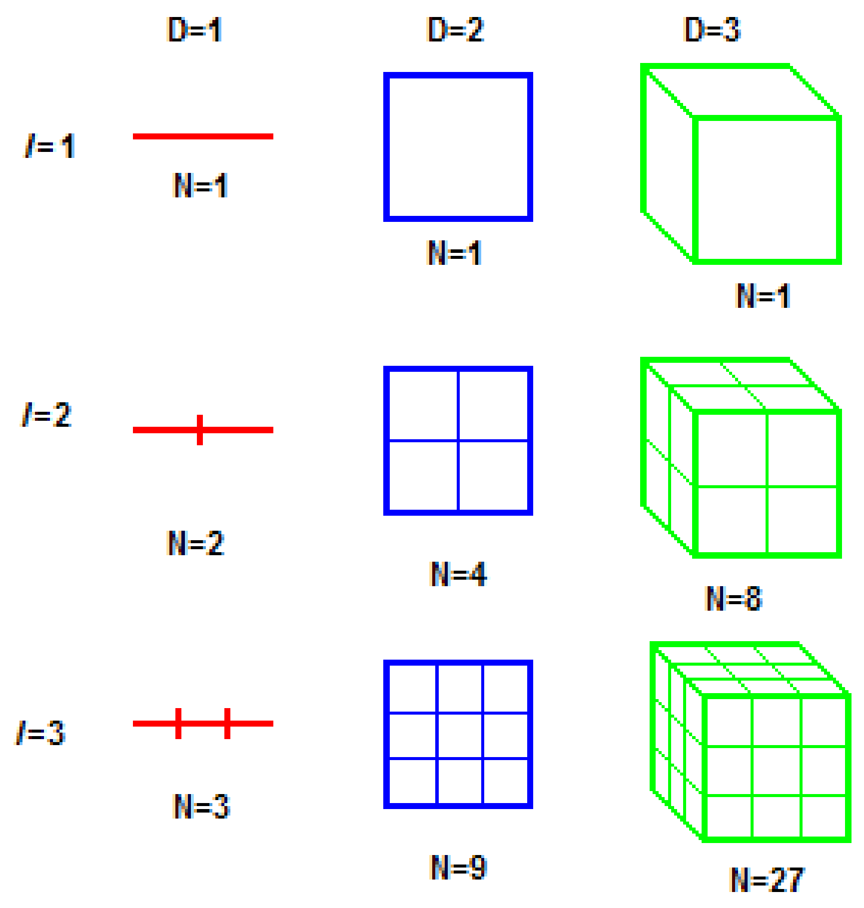


Image 14: Leaf morphology - venation. John Doe. Own work

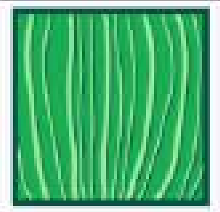
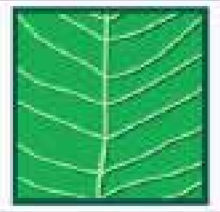
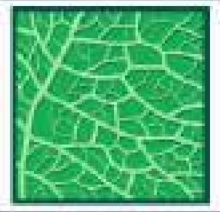
MECHANISM
LEAF VENATION

In reticulated patterns, which are the commonest, veins are arranged interconnected in a net-like pattern, and the main vein sometimes has the same size and thickness of the petiole, blended as a continuous line. Secondary veins branch from the midrib and extend toward the leaf margins. Smaller veins branch from the secondary veins (known as tertiary). Together it forms a dense pattern, a " scaffolding matrix imparting mechanical rigidity to leaves." This "matrix", the venation pattern, is perceivable in other types of venation pattern like the Transverse, Rotate, Dichotomous and Longitudinal, but it is valuable to understand numbers of primary veins, the other types of veins and the gaps between them arranged differently and accordingly to their context/characteristics (leaf could be thicker, larger, heavier, longer, tapered). Each vein collaborates individually with the structural support of the leaf, but their connection as a pattern is what provides the leaf an even distribution of any pressure applied to it.

Studies about fractal dimension (a fractal dimension is a ratio providing a statistical index of complexity comparing how the detail in a pattern (strictly speaking, a fractal pattern) changes with the scale at which it is measured. It has also been characterized as a measure of the space-filling capacity of a pattern in leaves) have shown the density of the pattern as directly related to some other leaf characteristics like size and rigidness. More flexible leafs have less dense patterns and rigid leafs have more dense patterns. Thicker leaves will display fewer veins and pattern density than a thin leaf. Bigger leaves also tend to display a greater hierarchy of veins, but sometimes instead of a dense pattern, it opts for thicker veins with long gaps between each vein.



These are the types of **venation patterns.**

Image	Term	Description
	Arcuate	Secondary arching toward the apex
	Dichotomous	Veins splitting in two
	Longitudinal	All veins aligned mostly with the midvein
	Parallel	All veins parallel and not intersecting
	Pinnate	Secondary veins borne from midrib
	Reticulate	All veins branching repeatedly, net veined
	Rotate	Veins coming from the center of the leaf and radiating toward the edges
	Transverse	Tertiary veins running perpendicular to axis of main vein, connecting secondary veins

https://en.wikipedia.org/wiki/File:Leaf_morphology_arcuate.png

image 15: Traditional notions of geometry for defining scaling and dimensionImage. Brendan Bryan. Own Work.
Image 16: Leaf Morphology - venation pattern. Debivort. Own Work

MECHANISM
LEAF VENATION

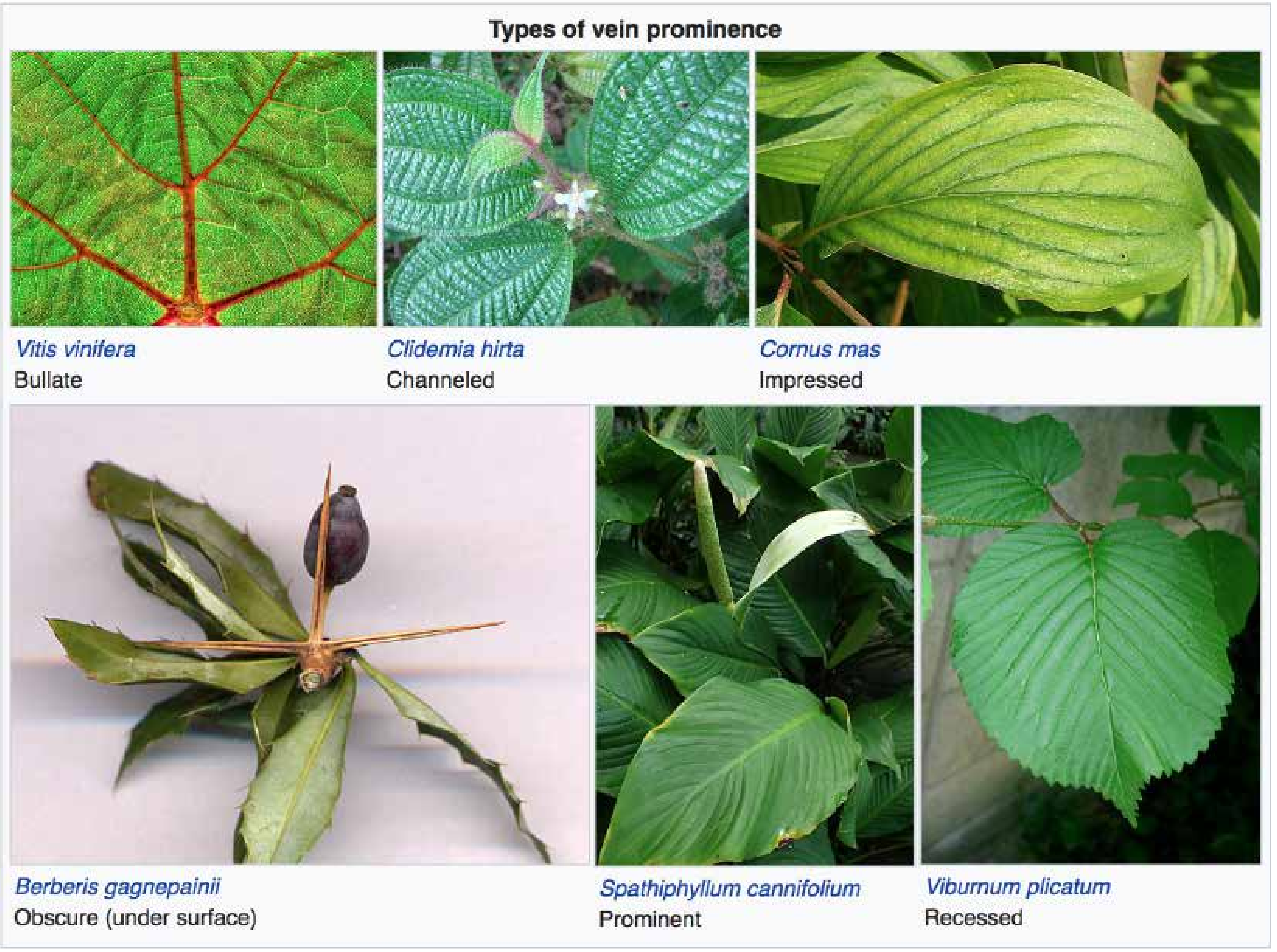


Image 17: Leaf topology. Many Artists Flickr

Many venation patterns are prominent on the top and at the bottom of the leaf, but there are other types of prominence.

These are characteristics of leaf venations that play a major role defining the leaves behave output:

1. Dimensions of vascular cells and of whole veins.

The larger the vein diameter, the greater mechanical support, resistance, and protection it provides to an area where veins cross each other. Leaves that have larger and thick petioles and midribs naturally do this effort to have a thinner and weaker lamina/surfaces, since their structure is guaranteed. Large leaves are mostly observed having a large and thick midrib. Long and large midveins can also provide the leaf the ability to fold at a specific place. This is done to reduce transpiration and reduce the mechanical load.

Image 18: Henriettea Leaf. E. P. Mallory Flickr 2013

2. Vein hierarchy

The hierarchy and the occasion where veins cross each other, in different angles, provides benefits including cost efficiency enhanced liquid flow, surface pressure equilibration and more tolerance to mechanical forces like damage and vein blockage on the main veins.

Image 19: Leaf Venation. Stefan klocek Flickr 2010

MECHANISM
LEAF VENATION

3. Vein tapering

Vein tapering is the reduction of the same vein thickness. It provides benefits for venation pattern hierarchy and an economic mechanical support from its base, it also allows some leaves to bend themselves towards the light. The density of the vein, its hydraulic capacity, helps the venation to be more or less resistant to mechanical support.

Image 20: Leaf thick stems. Moss. Flickr 2009

4. Vein length per unit area (VLA)

It is basically numbers of veins (primary to tertiary) occupying a specific area.
A high vein length per unit area provides tolerance for small damages and vein blockage. A high presence of veins in an area also helps it to become harder and more difficult for animals to eat. We could say that VLA is as the leaf's pressure.

Image 21: Eugenia aeruginea. B. P. Mallory Flickr 2013

5. Major vein density (VLA for primary veins)

Like the previous characteristic, this is the Vein per unit area of the major vein. Usually, it provides hydraulic and mechanical protection. It is more frequent in large leaves with thin laminae (and low leaf mass per unit area).
Naturally smaller leaves display a higher major VLA. The Major veins present in smaller leaves display better drought tolerance and protection and this is basically why there is an abundance of small leaves in dry and exposed habitats. Three major veins branching from the petiole is called “trivenation”.

Image 22: Leaf vein. Stefan Klocek Flickr 2014

6. Topology: major vein topology, looping

Studies have shown these characteristics are useful in minimizing the flow resistance relative to vein surface area, consequently, the pressure applied in each area. Leaves with more secondary veins can be highly foldable, but with a high energy expense for unfolding.

Image 23: Leaf Texture. Ggallice Flickr 2011

7.Leaf Size

The determination of a leaf size is related to the development of a venation pattern. Larger leaves tend to have larger petioles and major veins, which contain more numerous and larger vascular (xylem, phloem) conduits. It enhances transport capacity of a leaf’s VLA to make it independent of leaf size. Secondary and tertiary veins proportions, size, scale, and VLA were found almost unchanged from large to small leaves, it reinforces its main specific function of vascularization and liquid transport independently of a leaf’s size, and reinforces the major vein function of structural support.

Image 24: Big Mapple Leaf. Danna § curious tangles. Flickr 2013

DISCOVERING & DEFINING

LEAF VENNATION

Image 25: Tibouchina Leaves. Philip Bouchard. Flickr 2008

Venation Characteristics x Design Constrains

1. Dimensions of vascular cells and of whole veins.

Use of larger and thicker midribs might be useful to OKA's spoon since it is naturally bent. Also, an achievement of material reduction in the areas between these veins is a desirable advantage.

2. Vein hierarchy

Vein hierarchy must be used carefully in the spoon venation design, the pattern should have reduced hierarchy levels to match the production constraints.

3. Vein tapering

Interesting characteristic to be applied to the spoon's venation pattern, but it faces the challenge of not respecting a steady thickness, necessary for the production process to succeed. Vein tapering, if possible, could occur only at a small part of the spoon vein's tips to provide an aesthetic resemblance to a leaf.

4. Vein length per unit area (VLA)

A crucial characteristic of the spoon structural support and resistance, the vein pattern should provide a well-distributed vein per unit area, there should not be too many veins or veins that are too close. Pattern design should have the maximum of 2 to 3 types of veins. This trait, in addition to a Major VLA (next trait) pattern, should solve the problem of using this principle in favor.

5. Major vein density (VLA for primary veins)

Considering that a more simple but yet functional venation pattern will be developed for the spoon, the Major VLA characteristics helps deliver a venation pattern with reduced information and yet structural reinforcement. The Major VLA will be more useful than the VLA taking into consideration it matches the production constrains better. The fact that high Major VLA provides drought tolerance to leaves is interesting and matches the production constrains too, it means the spoon doesn't lose its structural reinforcement capacity when it's dry.

6. Topology: major vein topology, looping

major vein topology, loopingThe OKA's spoon is naturally bent, vein looping could be used to minimize the pressure/tensions concentrated on the bent surfaces. It's possible to confirm that applying the venation pattern only at the bottom of the leaf won't compromise the spoon's structural resistance.

7.Leaf Size

The major veins will be structurally useful for the spoon, the rest of it, if possible, secondary and tertiary veins will allow curves in its surfaces and fulfill the aesthetic/biophilic demand. The spoon is medium sized, compared to large and small leaves.

Image 26: Henriettea succosa. Alex Popovkin. Flickr 2007

DISCOVERING & DEFINING
LEAF VENATION > FIELD TRIP

According to the leaf venation traits presented in this research, it was possible to define the adequate characteristics.

Thick/Large Midrib

Low level of hierarchy complexity

Little to no vein tapering

Low level of VLA density

Increased level of Major VLA density

Vein looping presence

Venation visible at the bottom

Presence of cross-sectioned veins angles

No Herbivory signs on stems
(means its hard to eat, structurally strong)

The understanding of the leaf venation characteristics research allowed and stimulated a field trip to better observe, test and try to match the leaf venation traits and functions to the Spoon's context and constraints. Fortunately, in the field trip, it was possible to find a leaf venation pattern that matches the wanted characteristics of the spoon, the leaves of the *Melastomataceae plant family.*

DISCOVERING & DEFINING
LEAF VENATION > MELASTOMATACEAE

Surrounded by nature, with many leaves and characteristics, one type has found to be the most interesting. From broad to small leaves, a pattern of characteristics define this rigid, steady, firm and with no signs of bites/herbivory in its main stems plant:

The Melastomataceae Plant Family.

The Melastomataceae venation patterns fit most of the spoon constraints and needs.

Most of the Melastomataceae family leaves have its venation patterns only visible at the bottom. Its large midribs branches out into other large veins which in its turn arches toward the leaf tip (acrodromous venation type). The structure of 3 midribs (trivenation type) branching out of the petiole is commonly found on Melastomataceaes and it's a clear sign of Major VLA density and structural reinforcement for load distribution.
Its secondary veins run perpendicularly to the main vein axis and the tertiary runs perpendicularly to the secondary vein axis (transverse venation pattern). It covers all the leaf surface with cross-sectioned angles providing it a balanced load distribution.
The different lengths between the cross-sectioned angles of the leaf pattern allow it to bend or not, at specific areas.

Melastomataceae plants respect a leaf venation hierarchy complexity that, in most of the times, is visually low/reduced, where it is only possible to see the main and secondary veins. The visible veins are protuberant comparatively to the other smaller and “hidden” veins. Since the smaller veins are hard to see, it’s easily perceivable that the distance between each bigger vein is larger and has less tapering than other leaf types. The reduced hierarchy matches well with the OKA spoon’s constraint of having simplified vein patterns that don't compromise its leaf aesthetic resemblance.

The most interesting Melastomataceae plant found, was the Melastomataceae Tomentosa (top left image). It was chosen for its venation pattern because it basically has the shape and size of the OKA’s spoon and its veins are present in most of the reinforcement areas needed for the spoon.

Image 27: Melastomataceae Miconia tomentosa. F. A. Michelangeli. Flickr 2015
Image 28: Miconia Nervosa Triana. Alex Popovkin. Flickr 2015
Image 29: Melastomataceae Leaf. Larry-Abraham. Flickr 2011

Image 30: Edited image. Julio Glatt 2018

Translating biological characteristics into project guidelines.

This is a translation and abstraction of the biological terms to allow the development and application of the venation pattern emulation into the spoon's design.

The next step is the development of the emulated venation pattern in a vector software. During this process, there will be adjustments in the venation pattern design if necessary, but most importantly, the design principles defined here are the guidelines of the project.

BIOLOGY MELASTOMATACEAE LEAF	→	DESIGN OKA'S SPOON
Thick/Long Midrib	→	Thick/Long Veins
Low level of hierarchy complexity	→	Low level of hierarchy complexity
Little to no vein tapering	→	Little to no gradual reduction of vein thickness
Low level of VLA density	→	Low-density level of small veins per area
Increased level of Major VLA density	→	Increased density level of thick/large veins per area
Cross-sectioned vein looping presence	→	Veins must connect each other in cross-sectioned angles
Venation visible at the bottom	→	The pattern must visible only at the bottom
No Herbivory signs on stems (means its hard to eat, structurally strong)	→	Veins must occur at the most fragile and tensioned points

Illustrating the design principles/guide lines of the project

Once the guide lines are established, a series of drawings and illustrations are made to allow a better understanding and visualization of it. Drawing the design principles is important since the project output (the venation pattern) will be built graphically in a vector software. So basically, what is seen here in the project guidelines is similar to what we will get in the final product (the venation pattern).

DESIGN PRINCIPLES / GUIDELINES

1 - Thick/Long Veins

2 - Low level of hierarchy complexity

3 - Little to no gradual reduction of vein thickness

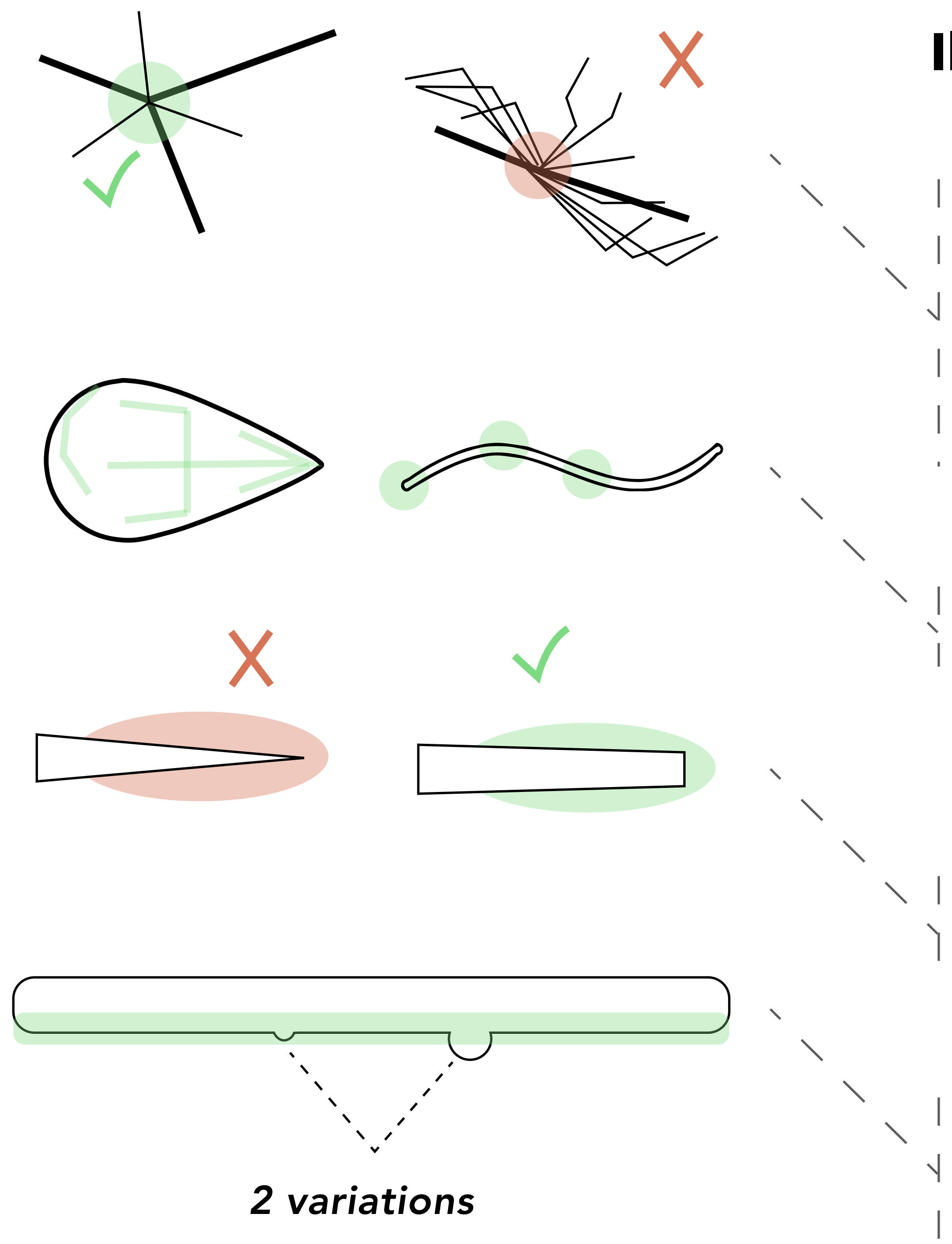
4 - Low-density level of small veins per area

5 - Increased density level of thick/large veins per area

6 - Veins must connect each other in cross-sectioned angles

7 - The pattern must visible only at the bottom

8 - Veins must occur at the most fragile and tensioned points



Illustrated design principle

2 - Low level of hierarchy complexity
4 - Low Density of Small veins per area
5 - Increased density level of thick/large veins per area
6 - Veins must connect each other in cross-sectioned angles

8 - Veins must occur at the most fragile and tensioned points

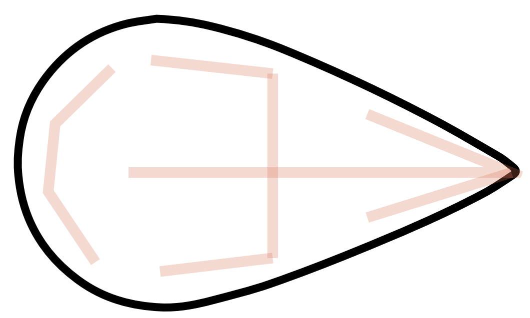
3 - Little to no gradual reduction of vein thickness

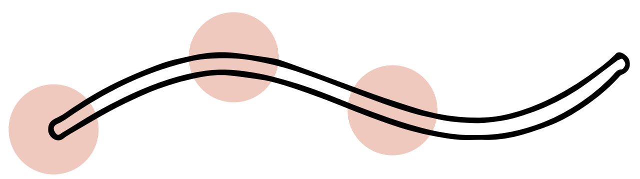
7 - Patterns must be visible only at the bottom
1 - Long/Thick Veins

DEFINING &EMULATING
VENATION PATTERN

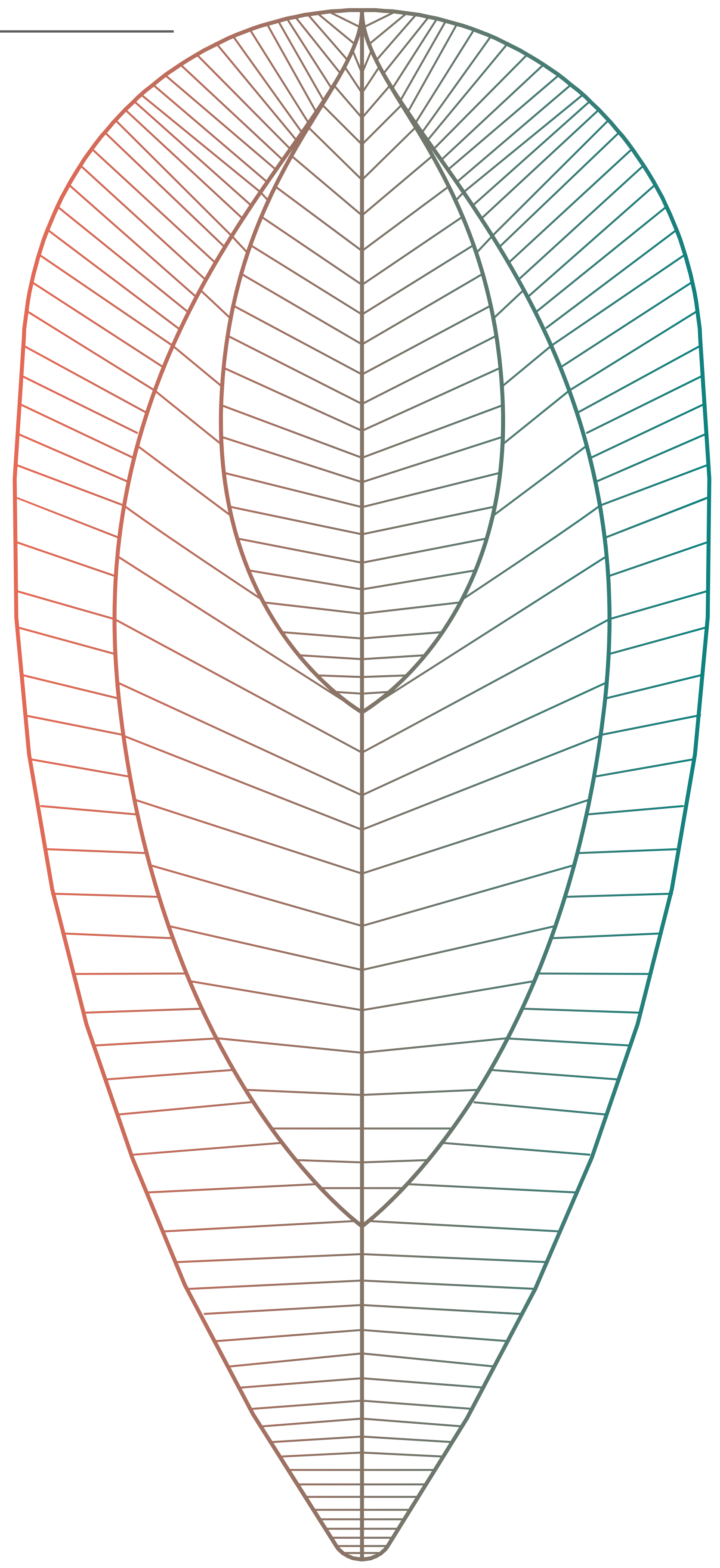
This is a vector image of the Melastomataceae tomentosa's venation pattern applied into the spoon shape and size. The venation pattern had adaptations with the purpose to cover the areas that need structural reinforcement.

The objective is pursued by using the guidelines listed below, and with the client's feedback about how the patterns should be to fit the production methods.





Check the evolution of the venation pattern emulation on the next page.



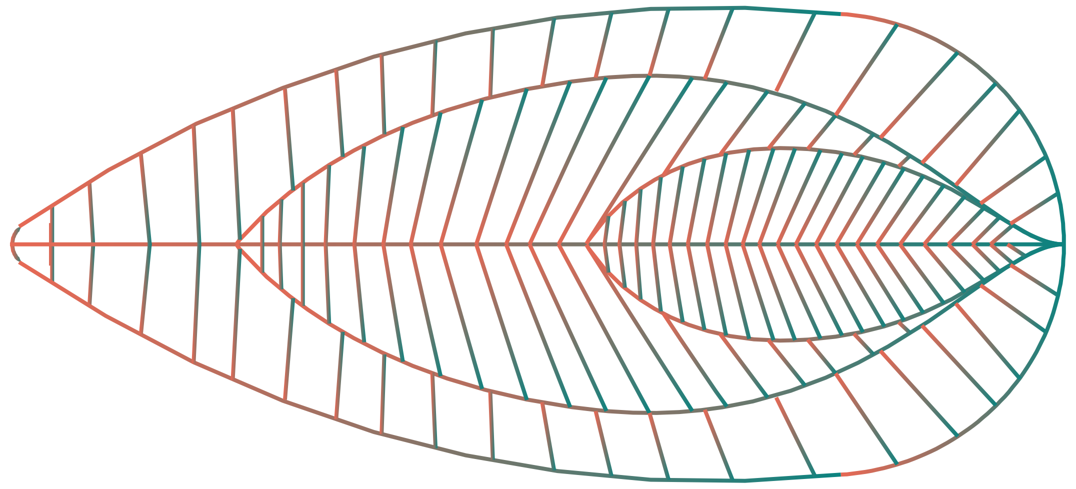
DESIGN PRINCIPLES / GUIDELINES

- Thick/Long Veins
- Low level of hierarchy complexity
- Little to no gradual reduction of vein thickness
- Low-density level of small veins per area
- Increased density level of thick/large veins per area
- Veins must connect each other in cross-sectioned angles
- The pattern must visible only at the bottom
- Veins must occur at the most fragile and tensioned points

DEFINING & EMULATING
VENATION PATTERN

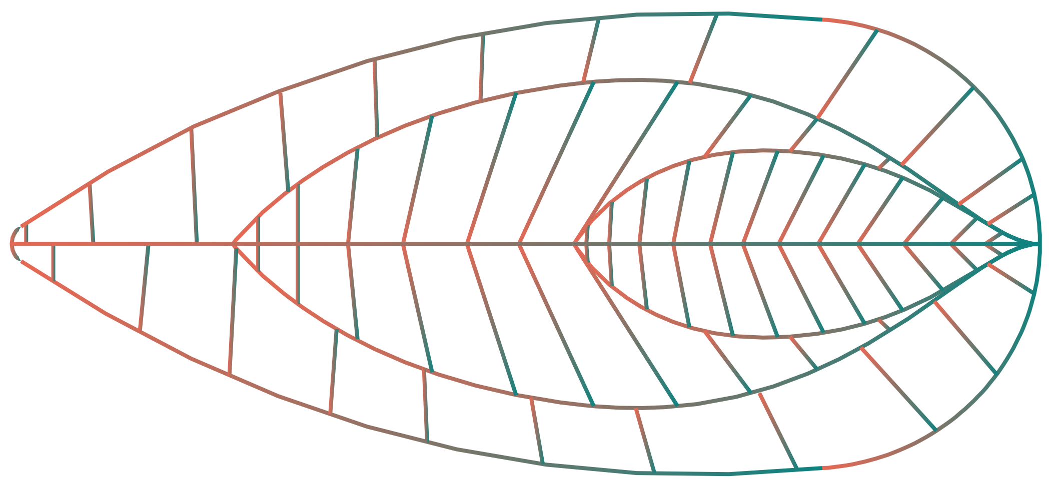
1

As the first image, this emulated venation pattern have too small vein density, and a higher hierarchy level.



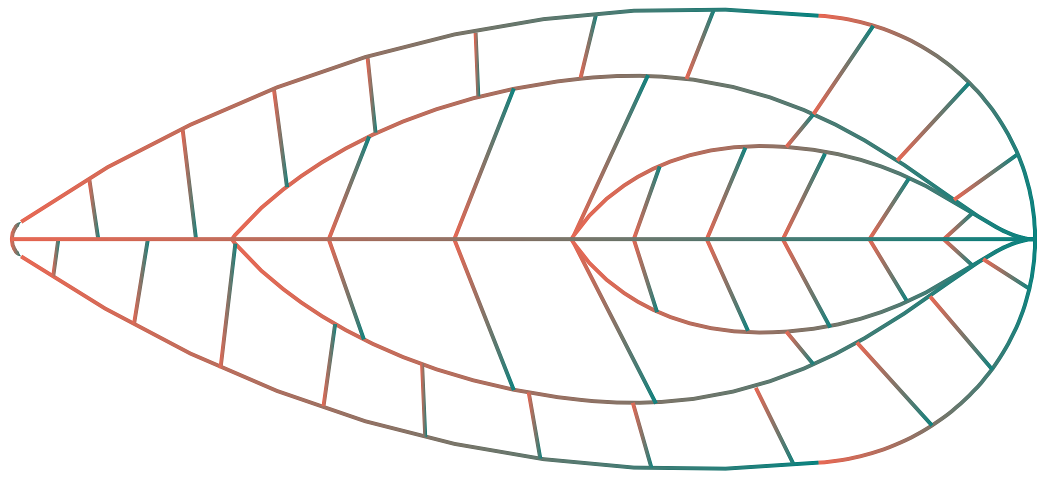
2

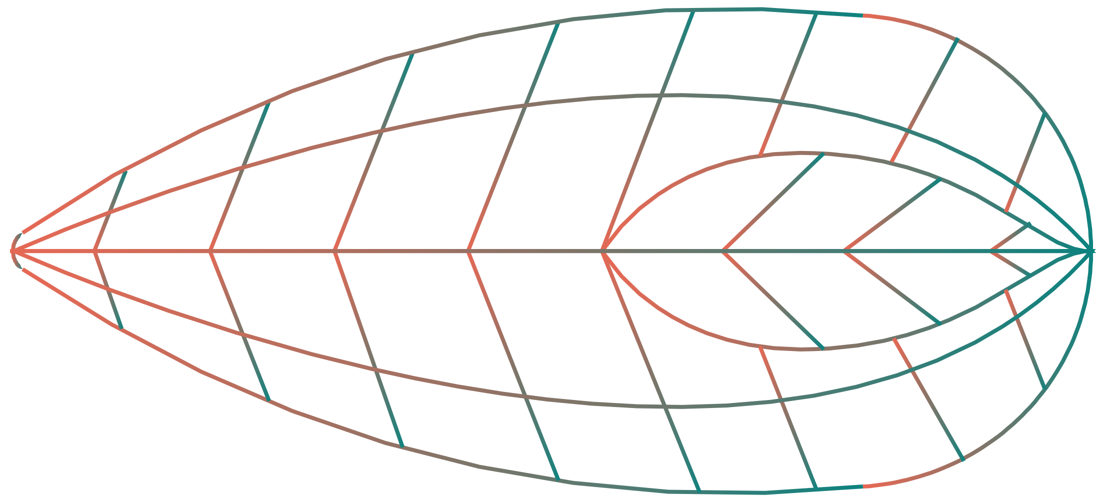
The small vein density is still present in many parts of the pattern, making it inadequate for the production methods. The level of hierarchy was not reduced.



3

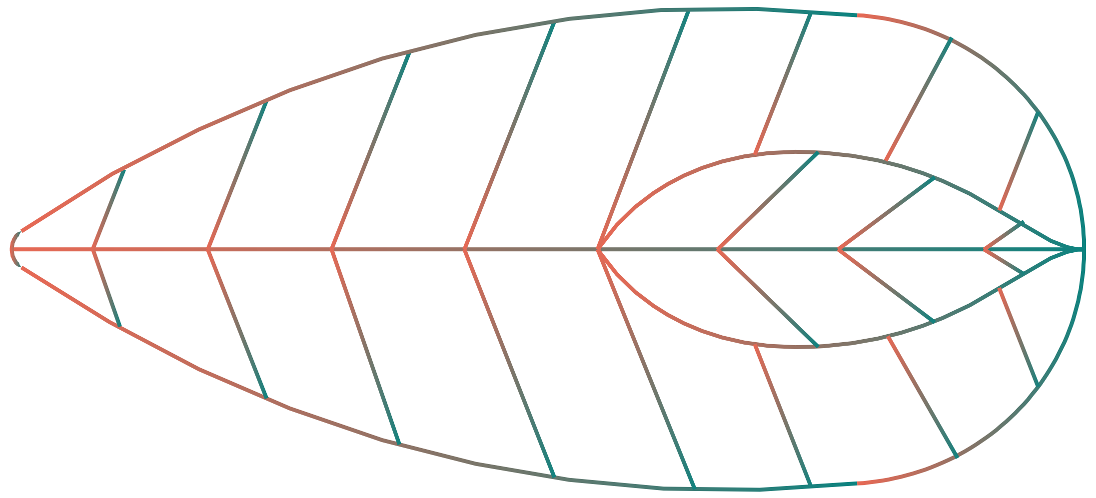
Hierarchy and small vein density greatly reduced, but there are still small spots where the density is still too much.





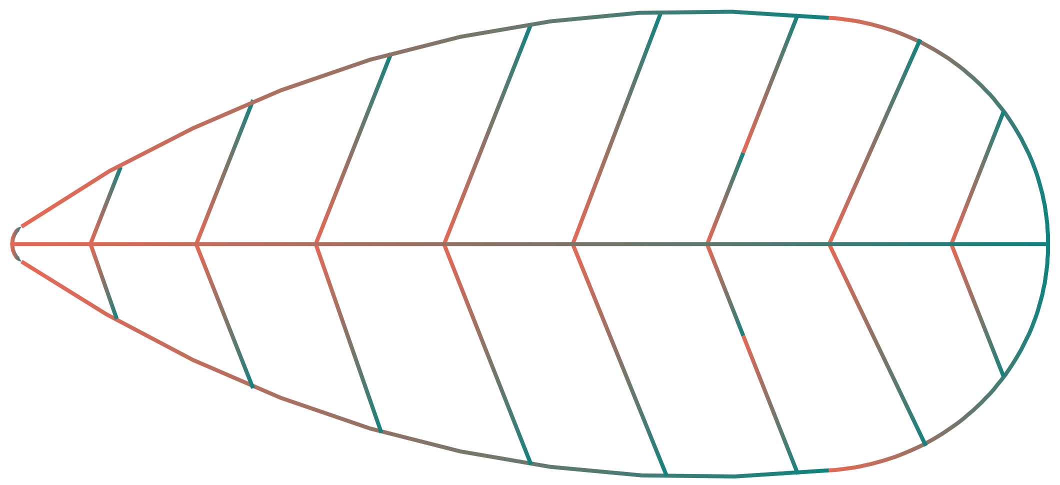
4

Like the previous pattern, this still has few areas where the small vein density is too high, but in addition, it has one of the large veins running differently through the leaf, with more area coverage and length.



5

This pattern has lost the high density per area of the larger veins, it looses structural reinforcement and it has also lost its resemblance to a leaf, comparatively to the previous patterns.

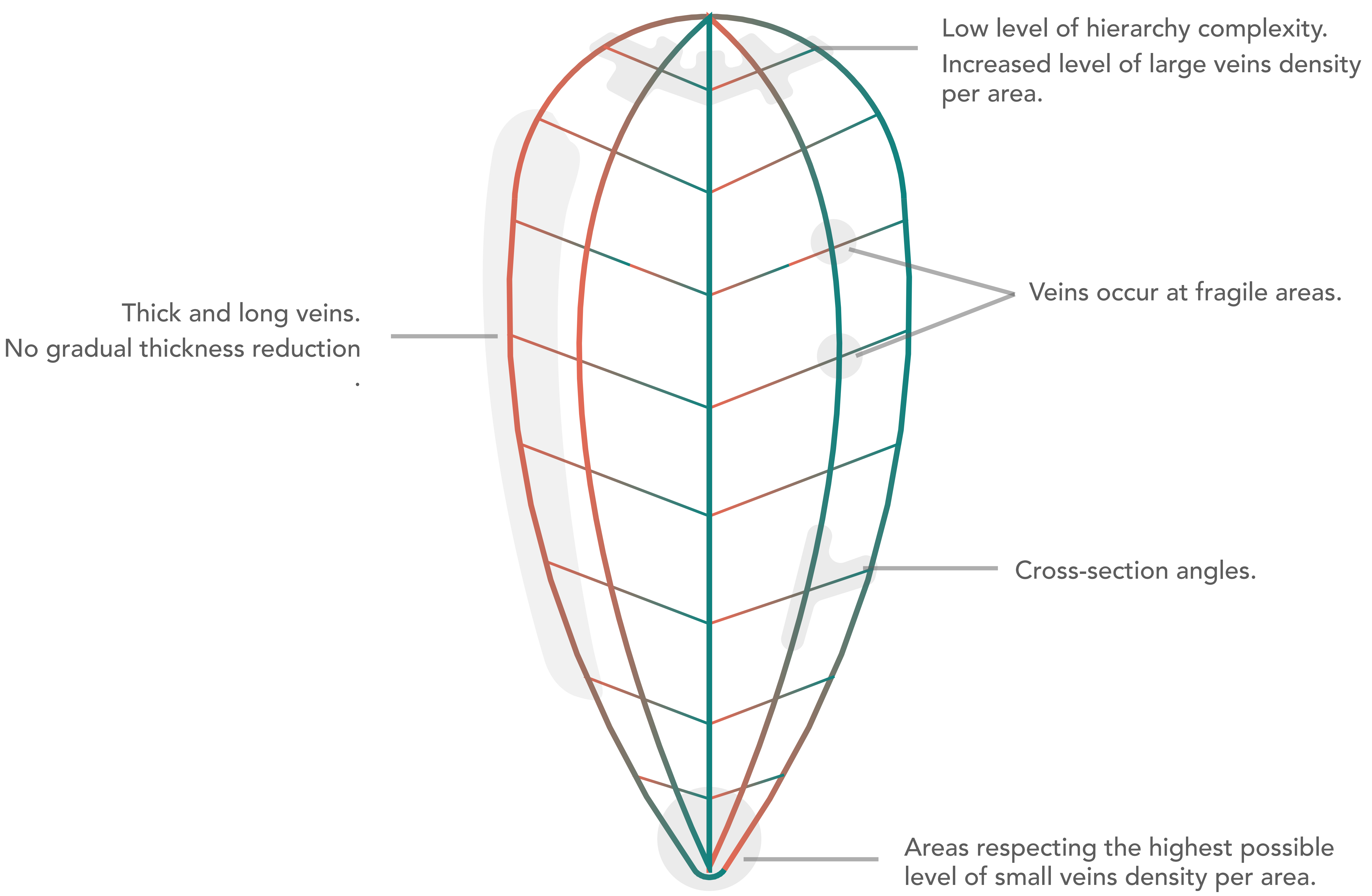


6

An exaggerated example of detail reduction in a pattern, it provides no leaf resemblance and no structural reinforcement to the spoon.

DEFINING & EMULATING
VENATION PATTERN

All the study here provided and the development of the emulated leaf venation pattern with client feedback allowed and converged to the definition and confirmation of this pattern (image at the right) as the final product.



DESIGN PRINCIPLES / GUIDELINES

Thick/Long Veins

Low level of hierarchy complexity

Little to no gradual reduction of vein thickness

Low-density level of small veins per area

Increased density level of thick/large veins per area

Veins must connect each other in cross-sectioned angles

The pattern must visible only at the bottom

Veins must occur at the most fragile and tensioned points

EVALUATING
LIFE'S PRINCIPLES

After the discovery of venation pattern's characteristics and mechanisms, an evaluation is made to ensure they are valid solutions to our design challenge and in accordance with sustainable/regenerative design principles. We are using Life's Principles as guidelines and evaluation method.

Five principles that stood out are:

1 Be Resource Efficient

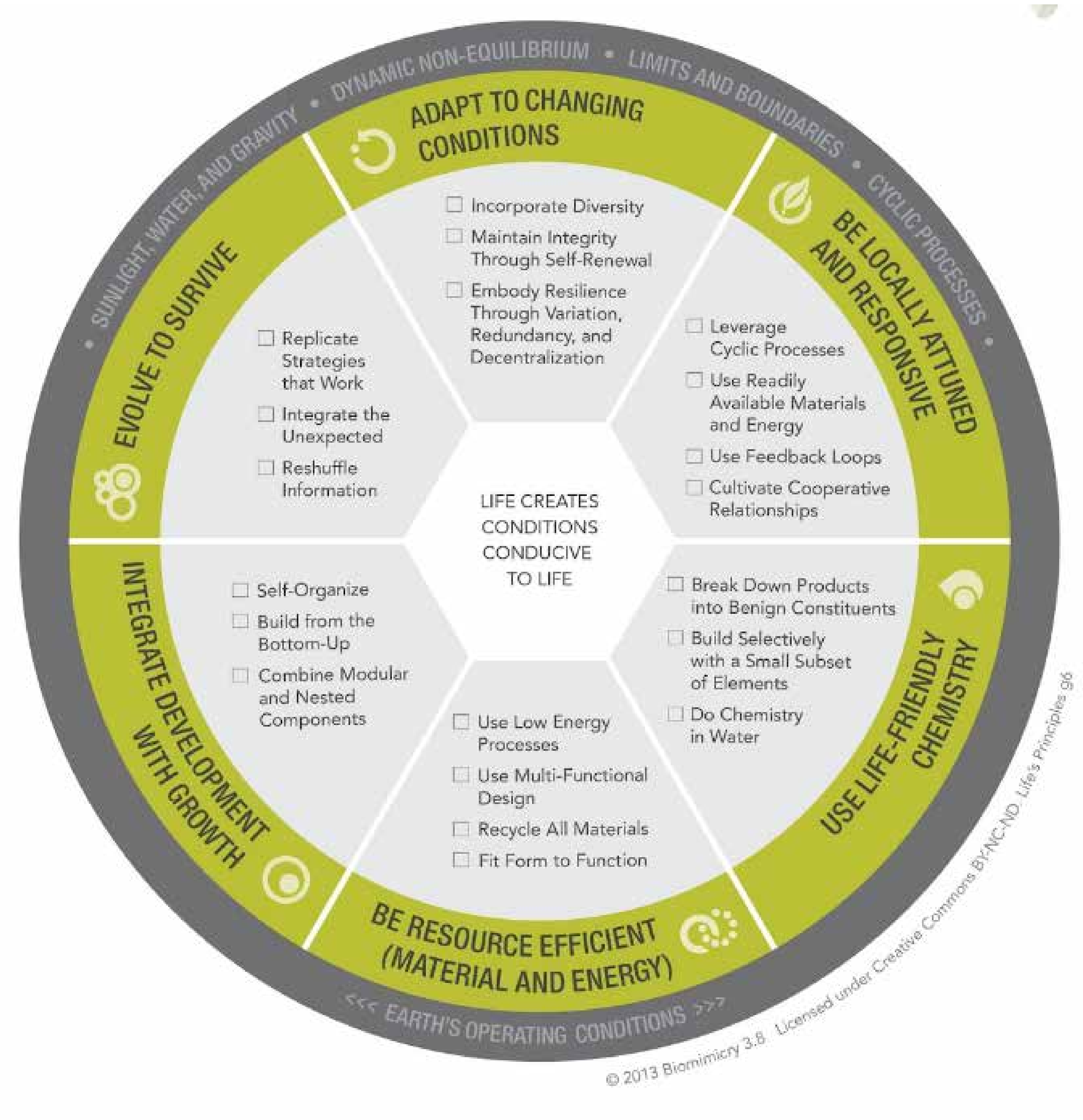
This is the core Life Principle present in this project, fitting the leaf venation pattern to its mechanical function will provide structural reinforcement with less material. It is also multifunctional accordingly to the OKA's objectives: leaf resemblance and structural reinforcement.

2 Integrate development with growth

The combination of each vein helps create a network that provides structural stability consequently.

3 Adapt to changing conditions

The replication of the same structure in varied sizes, thickness, hierarchies, spread all over the leaf surface grants it many structural abilities.



NEXT STEPS

EVALUATING<>PRODUCING

Vector pattern will be applied on the 3D spoon model and printed with a 3D printer for prototyping test

Make adjustments in vector pattern if needed and finally produce the OKA's Spoon. Other adjustments might be necessary after the final production, it is an continuous process of optimization and evaluation.

REFERENCES
RESEARCH

Sack, L., M. Caringella, C. Scoffoni, C. Mason, M. Rawls, L. Markesteijn, and L. Poorter. **"Leaf Vein Length per Unit Area Is Not Intrinsically Dependent on Image Magnification: Avoiding Measurement Artifacts for Accuracy and Precision."** Plant Physiology 166, no. 2 (2014): 829-38.

Larcher, Letícia, Maria Regina Torres Boeger, Alline Flores Brito, and Renato Goldenberg. **"Morfologia das domácias foliares de Miconia sellowiana Naudin (Melastomataceae)."** Biotemas 25, no. 1 (2011).

Boeger, Maria Regina Torres, Ciane Biu, and Renato Goldenberg. **"Arquitetura foliar comparativa de Miconia sellowiana (DC.) Naudin (Melastomataceae) em diferentes fitofisionomias no Estado do Paraná, Brasil."** Acta Botanica Brasilica 23, no. 3 (2009): 657-65.

D. Bagchi et al., **"Insights from the Plant World: A Fractal Analysis Approach to Tune Mechanical Rigidity of Scaffolding Matrix in Thin Films",** Advanced Materials Research, Vol. 1141, pp. 57-64, 2016

Rolland-Lagan, Anne-Gaëlle, Mira Amin, and Malgosia Pakulska. **"Quantifying leaf venation patterns: two-dimensional maps."** The Plant Journal 57, no. 1 (2009): 195-205.

Price, Charles A., Sarah-Jane C. Knox, and Tim J. Brodribb. **"The Influence of Branch Order on Optimal Leaf Vein Geometries: Murray's Law and Area Preserving Branching."** PLoS ONE 8, no. 12 (2013).

Roth-Nebelsick, A. **"Evolution and Function of Leaf Venation Architecture: A Review."** Annals of Botany 87, no. 5 (2001): 553-66.

Sack, Lawren, Christine Scoffoni, Athena D. Mckown, Kristen Frole, Michael Rawls, J. Christopher Havran, Huy Tran, and Thusuong Tran. **"Developmentally based scaling of leaf venation architecture explains global ecological patterns."** Nature Communications 3 (2012): 837.

Choong, M. F., P. W. Lucas, J. S. Y. Ong, B. Pereira, H. T. W. Tan, and I. M. Turner. **"Leaf fracture toughness and sclerophylly: their correlations and ecological implications."** New Phytologist 121, no. 4 (1992): 597-610.

Niklas, Karl J. **"A mechanical perspective on foliage leaf form and function."** New Phytologist 143, no. 1 (1999): 19-31.

"Leaf venation: structure, function, development, evolution ..." Accessed December 13, 2017. http://www.eeb.ucla.edu/Faculty/Sack/publications/Lawren%20Papers/SackScoffonti_2013_NP_TansleyReview.pdf"

Nix, Steve. **"How to Identify a tree leaf using shape, margin, and venation."** ThoughtCo. Accessed December 13, 2017. https://www.thoughtco.com/id-trees-using-leaf-shape-venation-1343511.

"Oka Bioembalagens - Biotecnologia." Oka Bioembalagens - Biotecnologia. Accessed December 13, 2017. https://www.okabioembalagens.com.br/.

Boundless. **"Leaves."** Leaves | Boundless Biology. Accessed December 13, 2017. https://courses.lumenlearning.com/boundless-biology/chapter/leaves/.