Fill up the bowl!

Leghold traps, limed rods, pit traps - insectivorous plants have come up with unusual strategies to obtain additional nutrients. **Axel Mithöfer** at the **Max Planck Institute for Chemical Ecology** in Jena is investigating how pitcher plants from Southeast Asia entrap and digest their victims.

TEXT **CATARINA PIETSCHMANN**

Plants that consume animals – imagine coming up with an idea like that! Evolution, though, doesn't suffer from qualms. Pitcher plants are extraordinary and have long been a source of curiosity and flights of fantasy.

Charles Darwin went as far as to dedicate an entire book to these plants, commonly referred to as carnivorous. Of the sundew's trapping mechanism, he wrote: *"It is surprising how minute a particle of any substance, ... if placed in actual contact with the surface of a gland, suffices to cause the tentacle to bend. [...] It is a much more remarkable fact that when an object, such as a bit of meat or an insect, is placed on the disc of a leaf, as soon as the surrounding tentacles become considerably inflected, their glands pour forth an increased amount of secretion."*

It's not just our fascination with plant carnivores that have attracted us; there are also purely practical ways of using them. In Malaysia, for example, the traps of the pitcher plant, *Nepenthes*, are filled with sticky rice, vegetables, or meat and eaten. On the island of Borneo, old pitchers that have lignified are used as storage vessels for food and drink or for steaming rice.

FLUID WITH MEDICINAL POWERS

The plants are even said to be good for your health. Indigenous peoples, for example, treat skin inflammations and digestive disorders with the digestive liquid from the pitchers.

Axel Mithöfer also has a practical use for insectivorous plants. "In summer, I place two or three sundew plants next to the fruit bowl. That deals with any problems with fruit flies."

The additional nutrition the plants get from animals helps them to keep up in nutrient-poor environments. That's why, if you have a carnivorous plant at home, you shouldn't fertilize it. "If they can meet their needs for nutrients using their roots, they form fewer traps and instead invest more energy in leaves for photosynthesis," explains Mithöfer.

Of all the insectivorous plants, the Venus flytrap, *Dionaea muscipula*, with its traps reminiscent of leghold traps, is the most spectacular. It is native to North American bogs and is the best known active trapper. The waterwheel plant, *Aldrovanda*, indigenous in Germany but now extinct there, does possess a very similar trapping mechanism to the Venus flytrap. Its leaves, however, are only a few millimeters in size, and the plant grows under water, making it relatively unknown. With its tentacles that twist around its prey, the sundew is also an active trapper.

The Venus flytrap snaps shut on its victims at a surprising speed for a

Photo: Anna Schroll

Under UV light, the trap of a pitcher plant resembles a filigree work of art. Insects are attracted by nectar on the rim of the pitcher and slip into the belly of the trap. The lid prevents rain from diluting the digestive fluid in the trap.

» Chitin receptors signal the presence of prey to the pitcher plants – in the true sense of the word, they taste their food.

plant. Mithöfer gives me a demonstration of the trapping mechanism in the greenhouse of the Max Planck Institute in Jena. He carefully strokes a fine twig over an open trap, touching the tactile trigger hairs inside it a few times. The plant has three of these hairs, barely visible to the naked eye, on each half of the trap leaf.

STRUGGLING IS DEADLY

The trap snaps shut in a tenth of a second. "If the fly were smart, it would stay motionless for two hours. The trap would then open, and it could fly off," explains Mithöfer. But staying standing still isn't in the nature of flies. Understanding why isn't hard. Caught between the trap leaves, it panics and struggles wildly to free itself.

Each time it touches a trigger hair, it generates a tiny electrical impulse, just like that in a nerve cell. "The plant sums the impulses to determine if it has actually caught living prey, or if only a drop of rain has landed on it," Mithöfer explains. "Two, three contacts are okay. But nine or ten means it's curtains for the fly!" A plant that can actually count!

While the trap leaves squeeze together tightly and crush the insect, the flytrap literally starts to salivate. Acid and digestive juices are secreted from glands in the trap, bathe the prey and dissolve it. The same glands then absorb what the hungry plant lacks in its nutrient-poor habitat: nitrogen and phosphate compounds.

The feast lasts several days. Then the trap unfolds again and spits out the "bones" – the indigestible chitin exoskeleton of the fly. In the wild, the next rain shower washes out the remains of the banquet.

The sundew does things entirely differently. If an insect lands on its leaves, which are covered with fine tentacles, it gets trapped by countless droplets of a sticky liquid. After this, the tentacles at the edge of the leaf first maneuver the animal into the middle of the leaf, where many of the glands that produce digestive juice are located. The leaf then slowly curls over the "meal", and the prey is digested.

There have been multiple independent instances of plants developing ways to consume animals. Depending on the expert you ask, there have been four to nine separate lines of development. The genomes of some species such as of a bladderwort, *Utricularia gibba*, and the Australian Albany pitcher plant, *Cephalotus*, have already been deciphered. In Wuerzburg, researchers are currently working on the genome of the Venus flytrap, and Mithöfer's team already possess that of one pitcher plant species of the genus *Nepenthes*.

NEW TASKS FOR PROTEINS

From their genes, it's clear that carnivorous plants have important things in common, even if they developed the ability differently. They all use the enzymes that evolution passed them down from their ancestors. "Plants have been exposed to herbivores and pathogens, such as fungi, for 400 million years. And that's the reason why they developed enzymes like chitinases that can break down the cell walls of fungi," said Axel Mithöfer.

It's a fortunate coincidence that the carapace of insects is also made of chitin. Carnivorous plants take advantage of this fact and simply re-deploy their existing tools, turning defensive enzymes into digestive secretions.

They can now use chitinases to break down the chitin shells of insects and get at the nutrients within. The plants get the nitrogen and phosphate from the bodies of the insects using proteins and enzymes that digest nucleic acids.

Mithöfer's particular field of expertise is pitcher plants. There are just over 120 species of the genus *Nepenthes* in

Above left The Venus flytrap has a sophisticated capture mechanism. The leaves have been repurposed as folding traps and contain trigger hairs, which send signals to the plant when an insect is trapped. Within fractions of a second, the two leaf halves snap shut and capture the prey.

Above right The various species of sundew – here the Cape sundew – in contrast rely on sticky traps. Looking like sweet nectar on red flowers glittering in the sunlight, the traps are actually covered with a sticky liquid designed to attract and hold insects.

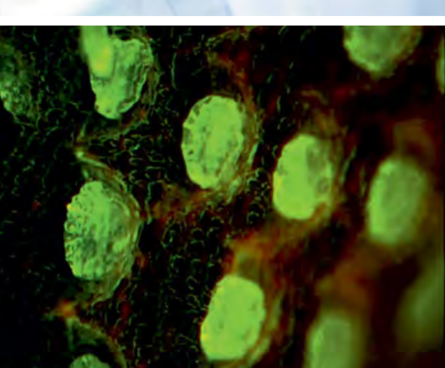
Below Alberto Dávila-Lara is a doctoral student in Axel Mithöfer's research group. The photograph shows him collecting nectar from the rim of a pitcher.

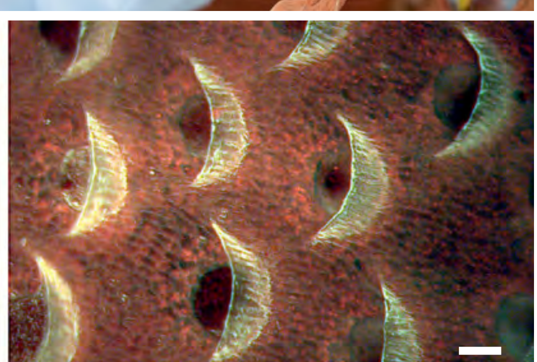
the humid tropical rain forests of Southeast Asia, most of them, climbing plants. Four species of *Nepenthes* grow in the greenhouse of Mithöfer's Institute in Jena.

Pitcher plants primarily prey on soil insects such as ants and termites. After a pitcher has matured and filled to a good quarter with fluid, the lid opens and the "hunting season" commences. At its rim, the pitcher secretes nectar, which becomes exceptionally slippery at high humidity. There's no way of gripping, even using the fine adhesive pads of insects feet. Incautious insects fall and drown in the fluid of the pitcher.

Axel Mithöfer investigates how digestive secretions are generated by feeding the pitchers with fruit flies and then placing nylon socks over them. "We do that to prevent flies from escaping or something else from falling into the pitcher."

And how do the pitchers sense that prey is near? Unlike the Venus flytrap, *Nepenthes* produces chemical rather than electrical signals. The plant's traps probably have receptors for chitin – the substance that forms the carapace of insects. While other plants use recep-



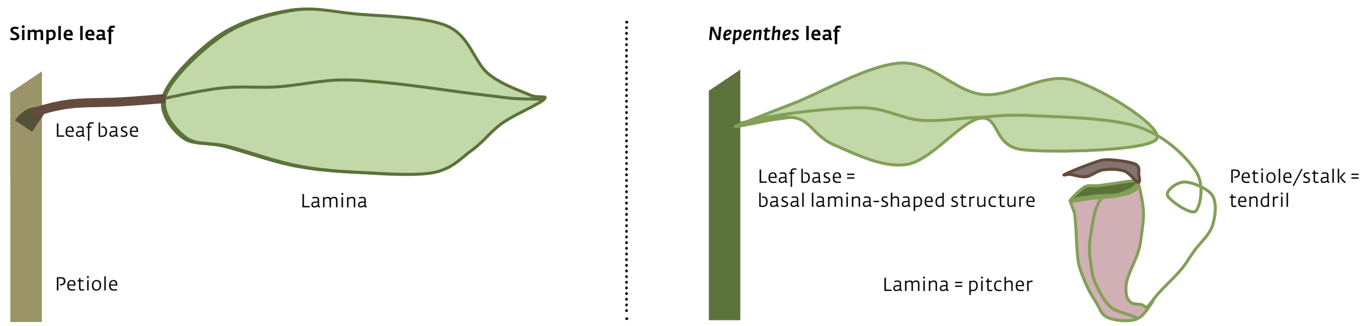


Above Using a sterile syringe, Alberto Dávila-Lara extracts digestive fluid from an unopened pitcher for further analysis.

Below left A fluorescence microscope reveals the glands in the pitcher wall that produce the digestive fluid.

Below right The glands lie in depressions of the epidermis and are covered by protruding hoods (The bar corresponds to one-twentieth of a millimeter).

Photos: Anna Schroll (above), MPI for Chemical Ecology (below, 2)



Metamorphosis from leaf to trap: over the course of evolution, the leaf base of an ordinary leaf in *Nepenthes* has developed into a basal structure and the petiole into the tendril of the pitcher. The leaf lamina eventually developed into the actual trap.

tors to detect predators, pitcher plants use theirs to sense the presence of prey. So, in the true sense of the word, they taste their food.

CHITIN PROMOTES DIGESTION

"As soon as the receptors detect the chitin of an insect's carapace, a signal cascade is triggered that activates the production of digestive enzymes," says Mithöfer. One of the cascade's most important signaling substances is the phytohormone jasmonic acid, which is also used to defend against predators. The digestive enzymes originate from glands in the lower third of the pitcher. These glands have two functions. "They both exude secretions and also transport the nutrients from the prey into the plant."

Typically, it's in their flowers that plants secrete nectar; *Nepenthes*, on the other hand, generates it at the rims of its pitchers. And the nectar isn't used to attract pollinators, but, instead, to catch prey. Unlike flower nectar, which can contain aromatic substances, pitcher nectar is entirely odorless. Even so, ants and beetles are tremendously attracted to it.

Mithöfer's doctoral student Alberto Dávila-Lara discovered that the rim of pitchers and the dot-like nectar glands on the body of the pitchers are not only sweet, they also glow violet under black light in the laboratory. Chemical analysis of the nectar revealed that this is probably due to a flavonoid. "Maybe it's this glow that attracts the insects," says Mithöfer.

To prove their hypothesis, Mithöfer and his team intend to test the behavior of ants by comparing how they behave presented with natural *Nepenthes* nectar and then with an artificial nectar lacking the flavonoid. To perform the experiment, they plan to fly an entire ant colony, including the queen, from Indonesia to Jena.

The pitcher fluid does already contain small amounts of enzymes before the first prey lands in it. But it can take between two and three days for enough digestive enzymes to form. "*Nepenthes* can take its time; the prey isn't going anywhere. It's a real gourmet!"

Mithöfer's team extracted the fluid from still young, unopened pitchers and discovered potassium chloride, trace elements, digestive enzymes, and naphthoquinones. As soon as the trap has caught something, it produces additional digestive enzymes and acid to activates the enzymes. The naphthoquinones have an antimicrobial effect and probably keep the juice free of germs for as long as possible. If too many insects are caught, the plant can no longer prevent bacteria from proliferating in the pitcher fluid. When this happens, the trap is broken down and discarded.

LEAVES CONVERTED INTO TRAPS

Even if the pitchers are usually strikingly colored and patterned, they're not the flowers, but elongated, widened, and specialized leaves – a beautiful example of how plant leaves can perform a variety of tasks. They hang from the plants in all stages of development: unripe and closed, active with the lid open, and shriveled and dead. If a pitcher is incapable of consuming food, it is usually only discarded when the plant has extracted as many nutrients as possible from it. A pitcher plant, after all, doesn't have resources to spare.

Not all carnivorous plants catch their own food. Some have a "delivery service" and reward the couriers with sweet rewards. There are also *Nepenthes* species that provide shelter for ants. They live sheltered in cavities of the pitcher plant and, in return, defend their landlady against predators. They themselves are unaffected by the digestive juices, which they simply swim through. >

Graphic: MPI for Chemical Ecology

Axel Mithöfer is investigating the signal cascades used by plants to protect themselves from predators and pathogens. Insectivorous plants have modified some of the molecules in the cascades to turn themselves into predators. A bushy angelica grows in the tea room of Mithöfer's research group, but ... it wouldn't harm a fly.

The plant also benefits from extracting the valuable nutrients from the waste material of the ants. In some instances, this type of nutrition can take on bizarre forms. "On the island of Borneo, tree shrews and rats sit on the rim of particularly large pitchers of certain *Nepenthes* species, lick sweet nectar from the inner surface of the lid – and simultaneously release their droppings into the pitcher. Another *Nepenthes* species provides daytime shelter for bats, whose excrement they then utilize," Mithöfer explains.

Besides carnivores and excrement feeders, pitcher plants can even be herbivores. *Nepenthes ampullaria* with its large pitcher openings, for example, waits for leaves to fall into its pitcher.

A plant that, during the course of evolution, consumes first light, then animals, and finally other plants – could there be any better way of demonstrating nature's almost infinite versatility? ◂

SUMMARY

- **There have been multiple instances of plant species independently evolving as carnivores to consume insects.**
- **Few plants species have evolved the ability to eat insects as new inventions; instead, they have tended to repurpose existing tools.**
- **Pitcher plants do not attract insects with the smell of the nectar they secrete on the rim of their pitchers. Instead, the nectar reflects ultraviolet light, and this is probably what attracts insects.**

GLOSSARY

Pitcher plants: At present about 120 *Nepenthes* species are known, and researchers are still discovering new species. Their range extends from Madagascar to New Caledonia and from China to Northern Australia. The leaves consist of a leaf base, a tendril, and the actual pitcher trap. Some species have traps up to 50 centimeters in size. Many *Nepenthes* species are threatened with extinction due to loss of habitat and illegal trade.

Venus flytrap: The traps of these carnivorous plants capture insects by snapping shut on them, after which they begin by exposing them to hydrochloric acid from gland cells. After a delay of a few hours, the glands also release digestive enzymes. The broken down nutrients are then absorbed by the same glands. These glands, are therefore similar in function to roots. This explains why only those genes that are typical for both leaves and roots are active in the trap cells.

Photo: Anna Schroll

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