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Report Blauwe Keten: Applications of proteins, amino acids and starch from duckweed

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Summary

Part of the Interreg Flanders – The Netherlands project 'Blauwe Keten' focusses on the applications of (duckweed. The main components in the dry matter part of duckweed are protein and starch. This report focusses on (potential) applications for protein, amino acids (the building blocks of proteins) and starch.

The main protein which is present in duckweed is Rubisco. This protein could be applied within the feed industry, the food industry but also in chemicals and materials. Within the feed industry it can be used as an ingredient for animal feed as a replacement for soya. In human food, proteins from duckweed could be applied for their gelation and foaming properties, or be used in protein shakes and as meat alternative. Protein can also be applied in chemicals and materials such as bioplastics, surfactants, coatings and glues.
The global protein market volume was over 5 million tons in 2017, where the value ranges from €100 per ton up to €7,000 per ton of protein, dependent on the purity and quality of the product.

One protein molecule can consist thousands amino acid molecules. In nature, over 500 types of amino acids are known. In the human DNA, 20 different types of amino acids can be found. Duckweed protein consists mainly out of 17 types (see paragraph 3.2 for the composition).
Due to the variety of amino acids, there are lots of applications possible for amino acids. Within chemicals and materials, amino acids are mainly used in plastics, rubbers, in the textile industry and as dyeing agent. Amino acids are also applied in the food and feed industry as dietary supplement or to enhance the flavour or fragrance. Higher purity and quality amino acids can also be used in pharmaceutical products or in cosmetics.
The global amino acid market volume was over 8 million tons in 2017, where the value ranges from €400 per ton for relatively low quality/purity amino acids up to €1,100,000 per ton of protein, dependent on the purity and quality of the product.

The other main component in duckweed is starch. Starch consists of glucose molecules. Applications for starch are mainly based on its binding, emulsifying, stabilizing and/or thickening functions. In foods it is applied for its thickening properties or for its properties as flavour enhancer and colorant. Due to its strengthening properties, starch is applied in the paper, packaging and textile industry. In the chemical industry, starch can be applied in surfactants, resins, biodegradable plastics, or for materials such as concrete admixtures, plasters and insulation. Starch can be used as precursor material in the synthesis of starch-based nano-particles. Furthermore in the pharmaceutical industry starch can be used as tablet disintegrant, release polymer, plasma volume expander, or used in bone tissue engineering and artificial red blood cells. Next to that it is applied in cosmetics, make up and health care products like in creams, lotions and toothpaste. Starch is also being used for the production of antibiotics, penicillin and vitamins.
The global starch market volume is expected over 49 million tons in 2014, where the value for 'regular' starch ranges from €60 per ton to €1,600 per ton, dependent on the purity and quality of the product. Starch specialties can even have a value of €90,000 per ton.

Samenvatting

In het kader van het Interreg Vlaanderen – Nederland project 'Blauwe Keten' wordt er onderzoek gedaan naar de toepassing van eendenkroos. De droge stof fractie uit eendenkroos bestaat voornamelijk uit eiwitten en zetmeel. Dit rapport beschrijft de (mogelijke) toepassingen van eiwitten, aminozuren (de bouwstenen van eiwitten) en zetmeel uit eendenkroos.

Het meest voorkomende eiwit in eendenkroos is Rubisco. Dit eiwit zou kunnen worden toegepast in de diervoeder- en voedingsmiddelenindustrie, maar ook in chemicaliën en materialen. In diervoederindustrie kan eiwit uit eendenkroos dienen als vervanger voor soja als eiwitbron. Kansrijke toepassingen in voedingsmiddelen zijn toepassing als bindmiddel, om producten luchtig te maken, in eiwitshakes en als vleesvervanger. In chemicaliën en materialen kunnen eiwitten uit eendenkroos mogelijk worden toegepast voor productie van bioplastics, oppervlakte-actieve stoffen, coatings en lijmen.
In 2017 was het wereldwijde marktvolume van eiwitten meer dan 5 miljoen ton, met een waarde variërend tussen €100 en €7.000 per ton, afhankelijk van de zuiverheid en kwaliteit van het eiwit.

Eén eiwit molecuul kan bestaan uit duizenden aminozuren. De natuur kent meer dan 500 verschillende typen aminozuren, het menselijk DNA bevat 20 typen aminozuren. Eendenkroos eiwit bestaat in ieder geval uit 17 typen aminozuren (zie paragraaf 3.2 voor de samenstelling).
Vanwege de variëteit van aminozuren in eendenkroos eiwit zijn er veel verschillende toepassingsmogelijkheden. In de categorie chemicaliën en materialen worden aminozuren toegepast in plastics, rubbers, de textiel industrie en in kleurstoffen. Aminozuren worden ook toegepast in voedingsmiddelen en in diervoederindustrie. Veelal als geur- en/of smaakversterker. Hogere kwaliteit aminozuren, aminozuren in zuivere vorm, kunnen ook worden ingezet in farmaceutische producten en cosmetica producten.
In 2017 was het wereldwijde marktvolume van aminozuren meer dan 8 miljoen ton, met een waarde variërend van €400 per ton voor relatief lage kwaliteit tot €1.100.000 per ton voor hoge kwaliteit aminozuren, afhankelijk van de zuiverheid en kwaliteit van het product.

Een ander bestanddeel van eendenkroos is zetmeel. Zetmeel is opgebouwd uit glucose moleculen. Toepassingen voor zetmeel zijn gebaseerd op de bindende, emulgerende, stabiliserende en verdikkende eigenschappen die zetmeel heeft. In voeding wordt zetmeel toegepast als bindmiddel, maar ook als smaakversterker of als kleurstof. Door zijn bindende eigenschappen wordt zetmeel ook veel toegepast in de papier-, verpakkings- en textiel industrie. In de chemische industrie wordt zetmeel toegepast in oppervlakte-actieve stoffen, harsen, biodegradeerbare plastics of voor materialen zoals cement en isolatiemateriaal. Zetmeel kan ook gebruikt worden in de productie van nanodeeltjes. Verder wordt zetmeel in de farmaceutische industrie gebruikt in medicijnen, plasma volume vergroter, botweefsel of kunstmatige rode bloedcellen. Daarnaast wordt zetmeel ook gebruikt in cosmetische producten als make-up, lotions, crèmes en tanspasta en bij de productie van antibiotica, penicilline en vitamines.
In 2014 was het wereldwijde marktvolume van zetmeel meer dan 49 miljoen ton, met een waarde voor 'regulier' zetmeel variërend tussen de €60 per ton tot €1.600 per ton, afhankelijk van de zuiverheid en kwaliteit van het product. Zetmeel specialties kunnen een waarde hebben tot €90.000 per ton.

Table of content

Summary 3
Samenvatting 4
1. Introduction 6
2. Applications of protein from duckweed 7
2.1 About proteins 7
2.2 Protein applications 7
2.2.1 Feed 8
2.2.2 Food 8
2.2.3 Chemicals and materials 8
2.3 Protein market 9
3. Applications of amino acids from duckweed 10
3.1 About amino acids 10
3.2 Amino acids in duckweed 11
3.3 Amino acid applications 12
3.4 Amino acid market 14
3.5 Amino acid prices 15
4. Applications of starch from duckweed 17
4.1 About starch 17
4.2 Starch applications 17
4.3 Starch market and prices 19
Bibliography 20

1. Introduction

Part of the research that is done within the Interreg Flanders – The Netherlands project 'Blauwe Keten' (translated: Blue chain), focusses on the growth and application of duckweed.
Duckweed is an interesting product because it is a rapidly growing water plant which is to be found on open waters such as ditches and ponds. Next to that it is also possible to grow it under controlled circumstances. Duckweed is also being tested as means of water purification since it grows on nutrients which are often present in residue streams.
What makes duckweed even more interesting is the fact that, under optimal conditions, it has the potential to grow up to 55 tons of dry matter per hectare per year. (1) Main part of this dry matter can consist of proteins, which can take up to 49% of the dry matter. (2)

Duckweed can be used for the production of biogas through anaerobic digestion. It can also be used as feed for cattle. Both possibilities were looked into as part of Blauwe Keten. The findings are described in the reports 'Biogaspotentieel restbiomassa spirulina en eendenkroos' (3) and 'Eendenkroos richting veevoer' (4). However, when looking from a biobased economy perspective it is more interesting to focus on products from duckweed that are higher up in the biobased pyramid (figure 1). For this, we need to look at the potential extraction, upgrading and application of the individual components within duckweed. The remaining fraction can still be utilized as feed or to produce biogas.

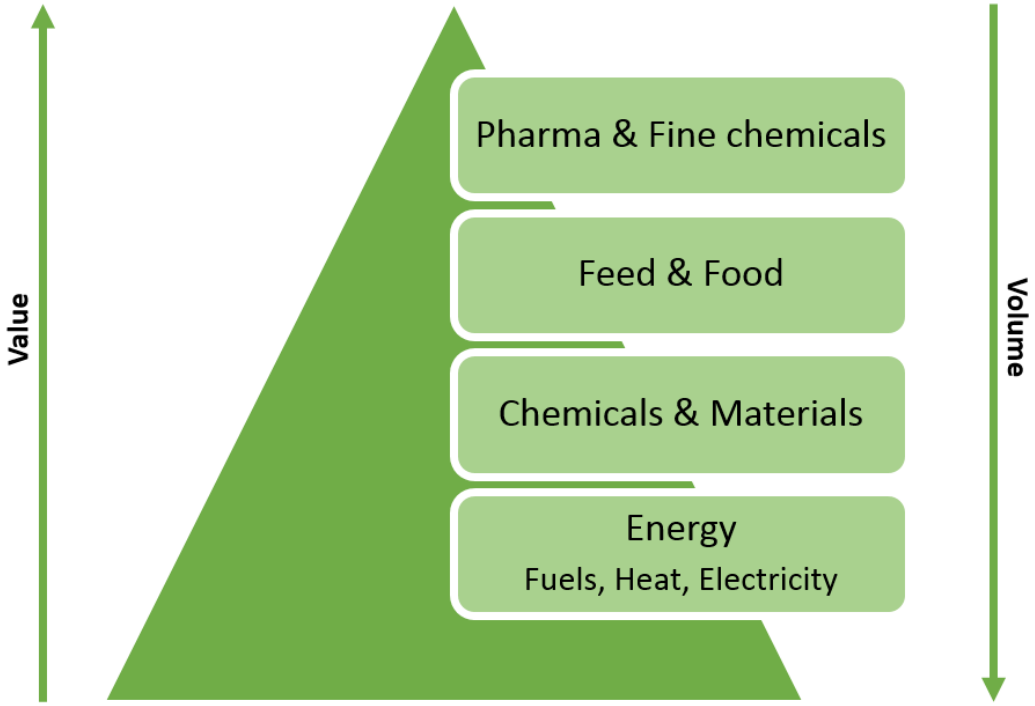

Figure 1: The biobased economy pyramid

When analysing the dry matter content of duckweed, the main part consists of proteins and starch. Then again, proteins can be broken down into amino acids. Therefore, this report will elaborate on the potential applications for proteins, amino acids and starch.

2. Applications of protein from duckweed

2.1 About proteins

Proteins are large molecules which are build-up of amino acids. The amount of amino acids in proteins can vary from 100 up to over 25,000 amino acids per protein molecule. Proteins are used in different types of applications and play an important role in the human body in the form of for example enzymes, transport proteins and as part of our DNA. In this chapter, we will look into the potential applications of proteins (from Duckweed). The main protein that is present in duckweed is Rubisco. Rubisco, probably the most common abbreviation for Ribulose-1,5-bisphosphate carboxylase/oxygenase, is regarded as the most abundant protein on Earth. It consist of an exceptional ideal composition of essential amino acids among plant protein and is therefore considered to be a large source of food protein in the future. (5)

2.2 Protein applications

There are several reports and articles about the use of proteins from duckweed (or other plants). However, most of these documents only describe the possibilities for applications. There are no commercial application described yet. Table 1 gives an overview of the possible applications of proteins from duckweed. Three main types of applications can be distinguished. Application in animal feed, application in human food and chemicals and materials. The company ABC Kroos, partner in the 'Blauwe Keten' project, is already able to produce proteins which are extracted from duckweed and can be applied in previously mentioned industries.

It has to be taken into account that (local) law and regulations might have influence whether or not the possible applications are allowed for duckweed protein. More information can be found in the report 'Eendenkroos: een stof vol mogelijkheden' (6).

Table 1: Possible applications of proteins from duckweed (7) (8) (9) (10) (11) (12) (13)

Category	Application
Feed	Ingredient for animal feed
Food	Protein shakes Gelation Foaming Meat alternative
Chemicals and materials	Bioplastic Surfactant Coating Glue

2.2.1 Feed

Protein from Duckweed can be used for the production of (high-grade) (mixed) animal feed. The possibilities depend on the protein content and composition. (9)

2.2.2 Food

Protein shakes
Whey protein is very popular in protein shakes and food nutrition for sportsmen and fitness. Protein from duckweed is a potential alternative for whey protein.

Gelation
Rubisco, the main protein in duckweed has very good gelation properties. Better than for instance soy and whey proteins. This property can be used in food applications where gelation is needed such as jam and fruit juices. (12) (13)

Foaming
Besides gelation properties, rubisco also has very good foaming properties. Better than for instance soy and whey proteins. These properties can be used in dairy based foams for applications such as coffee, shakes, ice-cream and desserts. (12)

Meat alternative
Rubisco can be applied in meat alternatives such as protein burgers. (11) (12)

2.2.3 Chemicals and materials

The report “Biobased Economy: de Potentie van Eiwitten voor Technische Toepassingen” (7) gives a complete overview of the possibilities to apply protein from for instance Duckweed in technical applications. The report also mention some industries that are interested in these applications.

Bioplastics
The production of bioplastics from Duckweed protein is not very obvious since it is much more logical to use biobased monomers such as lactic acid. Using these monomers leads to higher quality bioplastics since the characteristics of the product can be more specified. When using protein for the production of bioplastics, the product will be more dependent on the intrinsic characteristics of the protein. (7) The only feasible option for the use of duckweed protein in bioplastics is blending it with biobased monomers. (10)

Surfactant and coating
When proteins are partially broken down, you get peptides. Peptides often have surface active properties because they contain hydrophilic and hydrophobic parts. These surface active properties make them suitable for use as surfactant. Surfactants are applied in the cosmetic industry in for example shampoos, skin-care products and hair dyes, but also in paints to improve surface coating properties. The surface active properties are also interesting for application as binder in the coating industry. (7) (11) (14)

Glue
Proteins have a great adhesive strength and therefore can be used as glue. Using proteins in glue is already done for a long time. For instance in the paper industry (collagen, casein), plastics (soy-protein. (7) (11)

2.3 Protein market

When looking at the global protein market, a division is made between plant based and animal based protein. The total global market volume of protein was about 5 million tons in 2017. About 40% of the total volume is plant protein, as shown in figure 3.

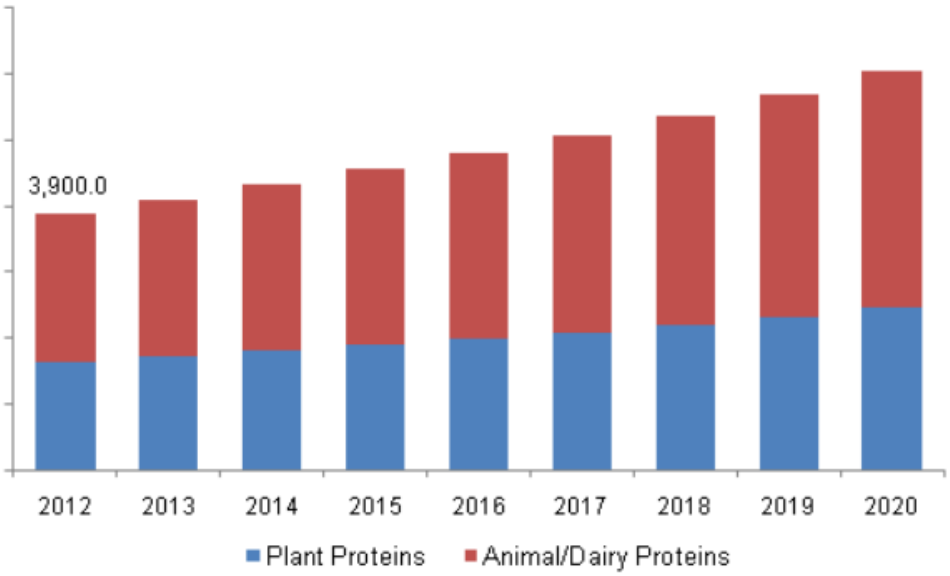

Figure 3: Global protein ingredients market volume by application, 2012-2020 (kilo tons) (51)

Based on figure 3, the expected global market volume will continue to grow the upcoming years to over 6 million tons by 2020. About 50% of this is applied in the food industry, a good 20% in the feed industry, a little less than 20% in infant formulations and the last 10% for pharma, cosmetics and (fine) chemicals. A rough estimation is that the global market value for protein was around 30 billion euro in 2017. For plant protein the global market value was between 5 billion and 8 billion euros.

Dependent on the quality of the protein and its composition, it will have a market value in the range of €100 to €7,000 per ton product for food and feed applications. (7) In a study of STOWA a price of €400 per ton was used for low-grade protein and €1,000 per ton for high grade protein. (8) (9) There are reports[1, 2] available with more detailed information about the volumes and market prices of protein (products), these are paid reports. Getting paid information is not part of the scope of this report. However, it is possible to get free samples of these reports, this is also where the information in this paragraph is based on.

[1] Protein Ingredients Market Size, Share & Trends Analysis Report By Product [Plant (Wheat, Soy Protein Concentrates), Animal (Egg, Milk Protein Concentrates)], By Application, And Segment Forecast, 2018 - 2025

[2] Protein Ingredients Market by Source (Animal and Plant), Application (Food & Beverage, Animal Feed, Cosmetics & Personal Care, and Pharmaceuticals), and Region - Forecast to 2022

3. Applications of amino acids from duckweed

3.1 About amino acids

As mentioned in chapter 2, proteins are molecules that are build-up from amino acids. This also means that you can break down proteins to get amino acids. When proteins are partially broken down to smaller molecules consisting up to 100 amino acids, the molecules are called peptides. Then again, you can break peptides down even further to amino acids as show schematically in figure 4.

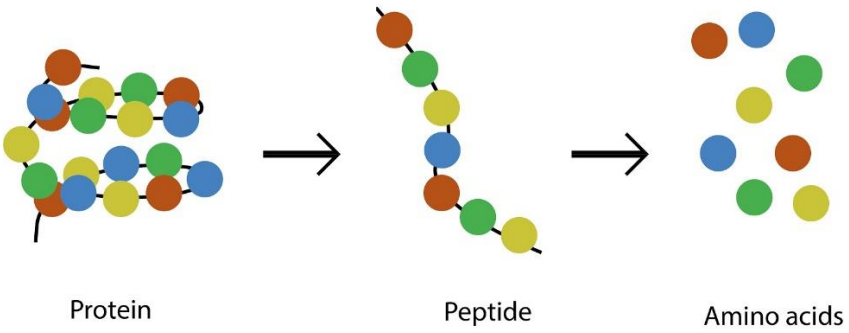

Figure 4: From protein to amino acids

Amino acids are molecules that contain an amine ($-NH_2$) group and a carboxyl (-COOH) group attached to a side chain, often called R group, which is specific for each amino acid. In nature, approximately 500 different amino acids are identified. The genetic material of the human body only consist of 20 different amino acids. From those 20 different types of amino acids, 8 types are marked as essential for humans (adults) since they can't be formed by the human body out of other molecules. The remaining 12 types of amino acids can be formed from other molecules by the human body in case the availability of those types does not meet the demand of the human body. Table 1 gives an overview of the 20 fundamental amino acids.

Table 2: Amino acids and their details

Amino acid	3-lettercode	1-lettercode	Essential	R group
Alanine	Ala	A		$-CH_3$
Arginine	Arg	R		$-CH_2-CH_2-CH_2-HN-(HN)=C(NH_2)$
Asparagine	Asn	N		$-CH_2-CO-NH_2$
Aspartic acid	Asp	D		$-CH_2-COOH$
Cysteine	Cys	C		$-CH_2-SH$
Glutamic acid	Glu	E		$-CH_2-CH_2-COOH$
Glutamine	Gln	Q		$-CH_2-CH_2-CO-NH_2$
Glycine	Gly	G		-H
Histidine	His	H		$-CH_2$-cyclo(C=CH-N=CH-NH)
Isoleucine	Ile	I	X	$-CH-(CH_3)-CH_2CH_3$
Leucine	Leu	L	X	$-CH_2-CH-(CH_3)_2$
Lysine	Lys	K	X	$-CH_2-CH_2-CH_2-CH_2-NH_2$
Methionine	Met	M	X	$-CH_2-CH_2-S-CH_3$
Phenylalanine	Phe	F	X	$-CH_2-Ph$
Proline	Pro	P		$-CH_2CH_2CH_2-$
Serine	Ser	S		$-CH_2-OH$
Threonine	Thr	T	X	$-CH(OH)-CH_3$
Tryptophan	Trp	W	X	$-CH_2$-cyclo(Ph-NH-CH=C)
Tyrosine	Tyr	Y		$-CH_2$-p-Ph-OH
Valine	Val	V	X	$-CH-(CH_3)_2$

3.2 Amino acids in duckweed

Amino acids are available in different sources, they can come from plant or animal protein. Important for the research in this project is the amount of amino acids in duckweed (protein), which represents the same as the composition of the protein in duckweed. This is given in table 2 where the values are given in grams per 100 gram of duckweed protein.

Table 3: Amino acid composition in different species of duckweed (g/100g protein) (15)

	Spirodela polyrhiza	Landoltia punctata	Lemna minor	Lemna gibba	Wolffiella hyalina	Wolffia microscopica
Ala	5.4	5.3	5.1	6.0	6.0	7.8
Arg	4.7	4.7	4.8	4.9	4.7	5.2
Asp	7.8	8.1	8.2	10.6	7.3	10.4
Cys	0.8	1.1	0.9	0.9	1.0	1.2
Glu	9.6	9.5	9.8	10.3	10.5	10.9
Gly	4.3	4.5	4.6	4.6	5.0	4.7
His	1.6	1.6	1.5	1.6	1.7	1.7
Ile	3.3	3.5	3.7	3.4	3.9	3.7
Leu	6.8	7.3	7.3	7.2	8.0	7.7
Lys	4.2	4.1	5.0	4.2	5.8	5.7
Met	1.6	1.6	1.6	1.6	2.0	1.6
Phe	4.0	4.5	4.4	4.3	5.1	4.2
Pro	3.5	4.1	3.8	3.9	3.7	3.6
Ser	4.1	4.0	4.1	4.2	4.3	4.7
Thr	4.2	4.1	4.0	4.0	4.2	4.7
Tyr	3.1	3.1	3.1	3.2	3.8	3.3
Val	4.4	4.6	4.6	4.5	4.8	4.9

Since the Blauwe Keten project is a cooperation between the Netherlands and Flanders, the most representative type of duckweed for this research is Lemna minor. Lemna minor is the type which is the most abundant type within this region. Figure 5 is showing the composition of duckweed protein in grams/100 grams of duckweed protein, which is equal to percentage.

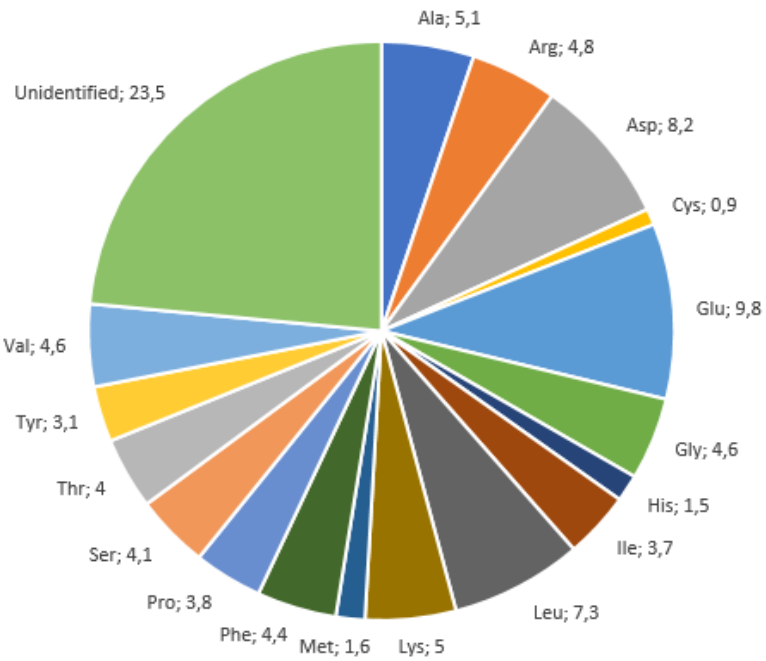

Figure 5: Amino acid composition of Lemna minor in %

3.3 Amino acid applications

As previously mentioned in chapter 2, when breaking down protein molecules to amino acids, the range of applications will be a lot bigger. The focus will only be on applications for the 20 types of fundamental amino acids. Because of the big diversity in possible applications, a distinction is made into sub groups related to the biobased pyramid. It has to be taken into account that (local) law and regulations might have influence whether or not the possible applications are allowed for duckweed protein. More information can be found in the report 'Eendenkroos: een stof vol mogelijkheden' (6).

Chemicals and Materials
Starting with the category of chemicals and materials, different types of amino acids can be applied in different kind of products. An overview is given in table 3.

Table 4: Applications for amino acids in chemicals and materials (7) (16) (17) (18) (19) (20) (21) (22) (23)

Amino acid	Product	Use in Chemicals & Materials
Alanine	Ethylamine	Dye intermediate
Arginine	1,4-butanediamine	Nylon-4,6
Asparagine	Maleic acid	Adhesion promoter
Aspartic acid	Acrylic acid	Plastics, coatings, elastomers, paints
Glutamic acid	1,5-pentanodiol	Plasticizer
Glutamic acid	Glycolic acid	Dyeing, tanning and flavouring agent, preservative
Glutamic acid	Butanolamine	Corrosion inhibition, catalyst applications
Glutamine	Acrylonitrile	Rubbers
Glycine	Oxalic acid	Dyes, bleaching, rust remover
Isoleucine	Isoprene	Rubbers
Lysine	ε-Caprolactam	Nylon-6
Lysine	γ-Butyrolactam	Vinyl-pyrrolidine synthesis
Phenylalanine	Styrene	Plastics
Proline	Vinyl pyrrolidone	PVP
Proline	γ-Butyrolactam	Vinyl-pyrrolidine synthesis
Serine	Ethanolamine	Herbicide, textiles, cosmetics
Serine	1,2-ethanediamine	Rubber, Pharmaceuticals, EDTA synthesis
Threonine	Isopropanolamine	Surfactants, lubricants, corrosion inhibitors
Threonine	Propionic acid	Pesticides
Tryptophan	Muconic acid	Fibres, plastics
Tryptophan	Aniline	Colorants
Tryptophan	Catechol	Photochemicals, printing
Valine	Isoprene	Rubbers
Valine	Toluene	Solvent, intermediate for benzoic acid, phenol

Food and Feed
Amino acids are necessary for human and animal species. A lot of food and feed already contain amino acids from their nature, but there are also other food and feed products in which they can be used as additives to enrich the nutritional value of a product. Table 4 gives some examples of amino acids that can be applied in the food and feed industry, however basically every type of amino acid can be used, for example in sport nutrition. The three most abundant amino acids on the market for food & feed are l-glutamate (the anion of glutamic acid), lysine and methionine (see paragraph 3.4).

Table 5: Applications for amino acids in food and feed (7) (18) (24) (25) (26) (27) (28) (29) (30) (31)

Amino acid	Product	Use in Food & Feed
Arginine	Ornithine	Dietary supplements
Aspartic acid	Aspartame	Sugar substitute
Aspartic acid	B-alanine	Dietary supplements
Aspartic acid	Fumaric Acid	Food additives, dyes
Cysteine	Acetylcysteine	Dietary supplement, cough medicine
Glutamic acid	Glycolic Acid	Dyeing, tanning and flavouring agent, preservative
Glutamic acid	Pyroglutamic acid	Dietary supplements, flavour enhancer
Leucine	C5 amine	Flavour, fragrances
Isoleucine	C5 amine	Flavour, fragrances
Lysine		Pork feed
Methionine		Poultry feed
Phenylalanine	Cinnamic acid	Flavour, fragrances
Tryptophan	Oxitriptan	Dietary supplements

Pharmaceuticals and fine chemicals

The top of the biobased pyramid is the category of pharmaceuticals and fine chemicals. The economic value per product is the highest in this category.

Table 6: Applications for amino acids in pharma and fine chemicals (7) (17) (19) (32) (33) (34) (35) (36)

Amino acid	Product	Use in Pharma & Fine chemicals
Asparagine	Acrylamide	Cosmetics
Asparagine	Fumaric acid	Pharmaceuticals
Aspartic acid	Soy peptides	Cosmetics (soaps, body sprays, detergents)
Glutamic acid	Gamma-aminobutyric acid	Pharmaceuticals
Glutamic acid	Glycolic acid	Cosmetics (anti-wrinkle products)
Glutamic acid	Sodium pidolate	Retains skin moisture
Leucine	Isopentylamine	Pharmaceuticals
Phenylalanine	Benzaldehyde	Fragrances, pharmaceuticals
Proline	Pyrrolidine	Pharmaceuticals
Serine	1,2-ethanediamine	Pharmaceuticals, EDTA synthesis
Serine	Ethanolamine	Cosmetics
Threonine	Allylamine	Cosmetics, pharmaceuticals, antimycoticum
Threonine	Propionic acid	Pharmaceuticals
Tyrosine	Hydroxystyrene	Fine chemical, electronics

As shown in tables 3, 4 and 5, there are a lot of (potential) possibilities for the application of amino acids that are present in duckweed. The tables are just showing some representative applications and don't give a complete overview of all possibilities.

As for duckweed protein, also for amino acids from duckweed it has to be taken into account that (local) law and regulations might have influence if the possible applications are allowed or not. Also for this matter the report 'Eendenkroos: een stof vol mogelijkheden' (6) can be consulted.
To become more concrete in interesting applications for amino acids out of duckweed, a more detailed market study is needed.

3.4 Amino acid market

When looking into the amino acid market, it is interesting to look further into the market volume. Regarding to this, some relatively recent data is found. The global market volume of amino acids in 2013 was almost 6.2 million tons. About a year later this data was available and extrapolated for the upcoming decade until 2022. (28) This market volume was also specified per type of amino acid as can be seen in figure 5.

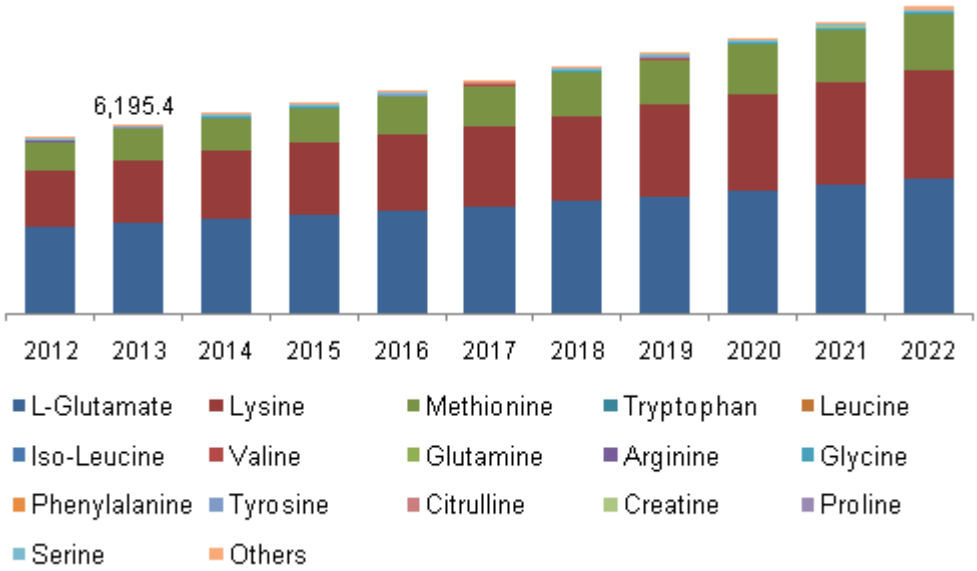

Figure 6: Global Amino Acids Market Volume By Product, 2012 - 2022 (kilo tons) (28)

Regarding to figure 5, the global market volume of amino acids is around 8 million tons in 2018. However, the market might be growing even more rapid than expected since the market already reached a volume of 8.5 million tons already in 2017 according to a report of the IMARC group. This report estimates the global market volume to be 11 million tons in 2023. (37)

What is even more important, in particular to this research, is that figure 5 gives also a specification per type of amino acid. The three most abundant amino acids on the market are l-glutamate (the anion of glutamic acid), lysine and methionine. The l-glutamate amino acid dominates the market with a share of roughly 45%, mainly due to its flavour enhancement properties. Lysine (roughly 35%) and methionine (roughly 15%) have a big share of the market value due to their use as animal feed additive. Lysine is mainly used in the pork feed industry whereas methionine is mainly used in the poultry feed industry. The remaining market share, roughly 5% or less, accounts for the other types of amino acids. (28)
As for Duckweed, glutamic acid is the most abundant amino acid (table 2). Lysine is only available half of the amount of glutamic acid, whereas methionine is in the top three of least available amino acids in Duckweed species.

3.5 Amino acid prices

Prices of amino acids can vary a lot, per type, but mainly due to the purity of the specific amino acid. In order to be able to provide an indication of these price ranges within this report, a price scan was performed. This was done by checking two different websites that sell amino acids.
The one website, alibaba.com, provides relatively low quality (low purity) amino acids for low prices, whereas the other website, sigmaaldrich.com, provides amino acids of higher quality for higher prices. The findings of this research is shown in table 7.

Table 7: Indication of prices per type of amino acid from alibaba.com and sigmaaldrich.com

Amino acid	Alibaba (€/kg)	Sigma Aldrich (€/kg)
Alanine	10	110
Arginine	12	92
Asparagine	9.15	203
Aspartic acid	8.75	110
Cysteine	11	226
Glutamic acid	0.90	70
Glutamine	6.90	509
Glycine	1.80	83
Histidine	9.65	976
Isoleucine	21	450
Leucine	1.10	418
Lysine	0.40	802
Methionine	2	100
Phenylalanine	18	277
Proline	9.8	876
Serine	0.90	575
Threonine	1.70	1,100
Tryptophan	31	1,089
Tyrosine	0.90	138
Valine	1.80	135

As table 7 shows, prices for amino acids ranges from €0.40 up to €21 per kg of amino acid in relative low purity. For relative high purity amino acid, this range is from €70 to €1,100 per kg. But what does this mean in practice for duckweed?

Table 8 (next page) is showing how much 1kg of duckweed protein is worth when it is extracted into separate amino acids. The amount of amino acids are based on the duckweed protein content for Lemna minor as shown in figure 5. The prices that are given in table 8 correspond to the price that has to be paid for that specific amount (grams) of amino acid. Again the price references are taken from alibaba.com and sigamaaldrich.com from table 7.

Table 8: Indication of the value of 1kg of duckweed protein, based on prices from alibaba.com and sigmaaldrich.com

Amino acid	gram/kg duckweed protein	Alibaba (€)	Sigma Aldrich (€)
Alanine	51	0.51	5.61
Arginine	48	0.58	4.42
Asparagine	n.a.	-	-
Aspartic acid	82	0.72	9.02
Cysteine	9	0.10	2.03
Glutamic acid	98	0.09	6.91
Glutamine	n.a.	-	-
Glycine	46	0.08	3.80
Histidine	15	0.14	14.64
Isoleucine	37	0.78	16.65
Leucine	73	0.08	30.51
Lysine	50	0.02	40.10
Methionine	16	0.03	1.60
Phenylalanine	44	0.79	12.19
Proline	38	0.37	33.29
Serine	41	0.04	23.58
Threonine	40	0.07	44.00
Tryptophan	n.a.	-	-
Tyrosine	31	0.03	4.28
Valine	46	0.08	6.21
Total	765	4.51	258.82

Summarizing table 8, it shows that 1kg of duckweed protein has a potential known value between €4.50 and €260 when extracted into single amino acids. These values will be higher due to the fact that only 17 of the 20 amino acids were verified. Together these 17 amino acids form 76.5% of the duckweed protein, the remaining 23.5% is unidentified.

4. Applications of starch from duckweed

4.1 About starch

Starch is part of the carbohydrates to be found in duckweed and is an interesting component for valorisation. The amount of starch can vary between 15% and 52% of the total dry weight of regular duckweed. There are researches in which the accumulation of starch is being studied and higher percentages of starch can be achieved up to 65%. (38) Starch (figure 7) is a polymer, formed of glucose molecules, with the molecular formula of $(C_6H_{10}O_5)_n$ and is available in large amounts in foods like potatoes, rice and maize. In plants, starch is stored as an energy backup. In case necessary, it can be broken down to glucose to become available as direct energy source for the plant.

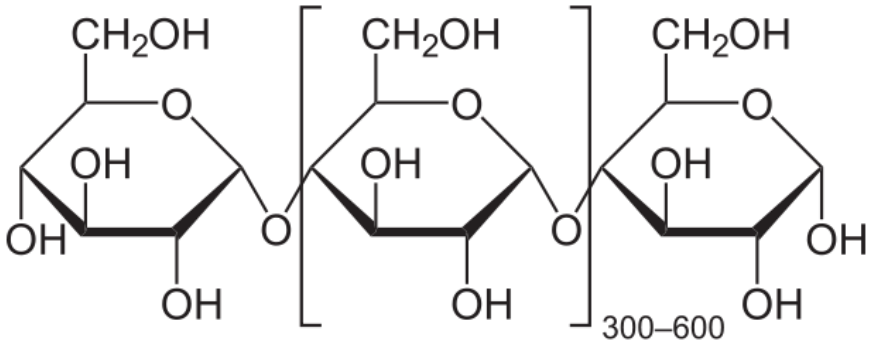

Figure 7: Starch, a molecule formed of hundreds of glucose molecules

4.2 Starch applications

Starch is applied in products based on its binding, emulsifying, stabilizing or thickening function. The main markets for starch are therefore within the food and drink industry, animal feed industry or within industrial applications. (39) Next to that it is also possible to apply starch in the pharmaceutical industry and in fine chemical.

Food and drinks
Starch can be applied in many types of industries. To begin with, it can be applied in foods and drinks. In drinks, it is used as flavour enhancer (due to its glucose components) or as colorant in multiple types of drinks such as soft drinks, fruit drinks and alcoholic drinks. In foods it is also applied as flavour and texture enhancer. Also its thickening and gelling properties is reason to apply it in soups, sauces, dairy products and desserts. When modified, starch can be a polysaccharide stabilizers which is used as additive in frozen food. (40) Furthermore it can reduce nitrate and nitrite levels and is therefore applied in meat and fish products. Starch is also applied in the feed industry, either as feed for cattle as well as feed for fish. (41)

Figure 8: Starch is being applied in many types of drinks as flavour enhancer or colorant (41)

Chemical and material applications
Next to the food and drinks industry, starch is also an important component for non-food industries like the paper industry. Starch is the product which gives paper a certain strength, while at the same time it improves the writing properties and printability of the paper. (40) Dependent on the type of paper, starch content can vary from 2% up to 8%. With the use of more recycled paper, the need for starch also increases since starch is necessary to preserve the fibre quality within the paper. (41) Within the packaging industry, starch is considered as one of the most promising materials to apply in packaging in the form of edible films and coatings. (42)


Figure 9: Starch is applied in the paper and cardboard industry (41)

When looking at the industrial applications, one of the applications of starch is the textile industry due to its strengthening properties. In the chemical industry, starch can be used in fermentation processes for the production of various types of chemicals. Within the chemical industry it can also be applied in surfactants, resins and biodegradable plastics. Starch is also being used for the production of biodegradable detergents. Another type of industrial applications lays within the construction industry where they make use of starch in several types of construction materials such as concrete admixtures, plasters and insulation. (41)

Pharmaceutical industry and fine chemical applications
Starch can be used as precursor material in the synthesis of starch-based nano-particles. Nano-particles are then again used in biomedical and industrial applications such as drug delivery carriers (43), biodegradable edible films and fluorescence bioimaging. Furthermore in the pharmaceutical industry starch can be used as pharmaceutical excipient, tablet disintegrant, release polymer, plasma volume expander or used in bone tissue engineering, artificial red blood cells. (44)

As last but not least, starch is used in pharmaceuticals. Within pharmaceutical products it is applied most of the times because of its binding and sweetening properties. Next to that it is applied in cosmetics, make up and health care products like in creams, lotions and toothpaste. Starch is also being used in the production of antibiotics, penicillin and vitamins. (40) (41)

It has to be taken into account that (local) law and regulations might have influence whether or not the possible applications are allowed for duckweed starch. More information can be found in the report ‘Eendenkroos: een stof vol mogelijkheden’ (6).

4.3 Starch market and prices

Starch market
Regarding to the starch market, there is data about starch derivatives which was over 49 million tons in 2014. (45) and data that says the European starch derivatives market volume was equal to the European starch market volume. (46) Therefore it is assumed this the global market volume for starch is also equal to the global market volume of starch derivatives. More information can be found in paid report(s)[3].

Starch prices
When looking at the prices for starch, the Danish International Starch Institute trading website was consulted. This website is a market for buyers and sellers of starch (products). The website shows starch coming from different sources such as cassava, corn, rice or potato. The prices for starch vary between €60 per ton for potato starch up to €1,600 per ton also for potato starch.
Again, the price difference will be based on quality/purity of the product. For example biodegradable starch is also offered for €2,100 per ton and starch specialties for €90,000 per ton.
A rough average for 'regular' (wheat-, cassava-, corn-, rice- or potato) starch is in between €200 per ton and €900 per ton. (47) (48)

[3] Grand View Research. Protein Ingredients Market Size, Share & Trends Analysis Report By Product [Plant (Wheat, Soy Protein Concentrates), Animal (Egg, Milk Protein Concentrates)], By Application, And Segment Forecast, 2018 - 2025. s.l. : Grand View Research, 2017

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