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Common ivy (*Hedera Helix L.*) as a novel green resource in an urban biorefinery concept

Willem Vercruysse[a], Bernard Noppen[a], Marijke Jozefczak[b], Michiel Huybrechts[b], Elien Derveaux[a], Bart Vandecasteele[C], Ann Cuypers[b], Wouter Marchal[a], Dries Vandamme[a]*

[a]Analytical and Circular Chemistry, CMK, IMO, Hasselt University, Agoralaan Building D, 3590 Diepenbeek, Belgium;

[b]Environmental Biology, CMK, Hasselt University, Agoralaan Building D, 3590 Diepenbeek, Belgium;

[c] Plant Sciences Unit, Flanders Research Institute for Agriculture, Fisheries and Food (ILVO), Burg. Van Gansberghelaan 109, 9820 Merelbeke, Belgium;

*dries.vandamme@uhasselt.be

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Abstract

Common ivy (CI) or *Hedera Helix* L., is a clinging evergreen vine which can be cultivated on any vertical surface (walls, fences, tree trunks, etc.). In Europe, CI has been recommended by governments to plant in urban areas because it lowers urban heat island effects and improves urban air quality. Regular trimmings of these vertical greenery systems would be necessary, which would yield a potentially interesting novel biomass resource for urban bio-refinery concepts. Furthermore, CI extracts contain pharmaceutically active compounds (e.g., hederacoside C and α-hederin), which constitute the active components of commercially available cough syrups. Moreover, research on their suitability to treat (lung) inflammations and suppress cancer tumor growth is ongoing and shows promise. CI extracts also demonstrated potential for their application in the agricultural industry to serve as anti-fungal agents. Recently, post-extracted residues of CI have shown to be a promising feedstock for green fertilizer production via slow pyrolysis. Moreover, a provisional sustainability assessment indicated that the proposed process would be both carbon and energy-negative. Therefore, a novel circular biorefinery approach is proposed, which entails the lifecycle of CI, from cultivation in vertical ecosystems via refinery into bioproduct(s) and valuable nutrients, back into soil.

Introduction

Our global population is forecasted to increase up to 9.7 billion in 2050[1]. By then, 67% of the world's population will reside in urban areas[2]. This increased urbanization poses several societal and environmental challenges. Firstly, urban citizens' health is threatened by atmospheric pollution[3]. Moreover, the urban heat island effect, the phenomenon in which urbanized areas experience higher temperatures than the outlying areas, contributes to increased mortality, especially in the older and poorer sections of the city-dwelling population[4]. Lastly, cities are significant sources of greenhouse gas (GHG) emissions[5], derived from all parts of the urban society, from the populace utilizing their fossil-fueled vehicles to enterprises fueling their energy-intensive production processes. In the last decade, one solution has come forward which could address these environmental challenges all at once: urban greenery[5]. Green walls, in particular, have proven to lower overall city temperatures[6,7], effectively adsorb significant parts of atmospheric pollutants[8,9] and incorporate large amounts of carbon dioxide during their growth[10]. Moreover, urban greenery has positive effects on the mental health of the residents[11]. All of the above would improve the life quality of residents in urban environments.

The transition towards a circular economy should also be driven by the development of new biomass-based bio-refinery processes, which results in the production of sustainable bioproducts[12]. Common ivy (CI) is a particularly interesting plant species to be applied in the green walls of our future cities. During its growth phase, it improves urban air quality (indoors[13] and outdoors[8]) while decreasing the urban heat island effect[14,15]. Cultivating CI in these green walls would yield substantial quantities (estimated to be 2 kg per m² on a yearly basis) of trimmings which require further downstream processing in a next phase. As it stands, these trimmings have shown to possess significant quantities of extractable pharmaceutically active compounds[16]. Extracts of CI are commercially applied as cough syrup (e.g., Prospan®) and possess anti-oxidant[17], anti-inflammatory[18], anti-carcinogenic[19], and anti-fungal properties[20]. A subsequent phase in the proposed bio-refinery process uses the spent (extracted) CI residue stream as a feedstock for bioproduct manufacturing. The application potential for the fractionation of spent CI trimmings into its lignocellulosic fractions (hemicellulose, cellulose and lignin) is discussed. However, the only reported cases where novel bioproducts were made from CI trimmings regarded the production of biochar from raw and spent CI waste, in which the oil and gas-fractions would be used for energy generation[21]. Moreover, a subsequent study[65] described a final step in the proposed bio-refinery process, which entailed the upgrading of biochar to advanced carbon products. This study aims to provide a perspective on the feasibility of the proposed bio-refinery approach (Figure 1). Each of the sections in this perspective will envisage one of the phases in the cascaded bio-refinery process and summarize the current knowledge concerning the suitability of using CI as a bioresource for each of the intented applications. To conclude, a provisional sustainability assessment (based on carbon and energy balances) will be provided to estimate the environmental impact of the proposed process. As such, this perspective will give insight into the applicability of CI as a feedstock for a novel bio-refinery process.

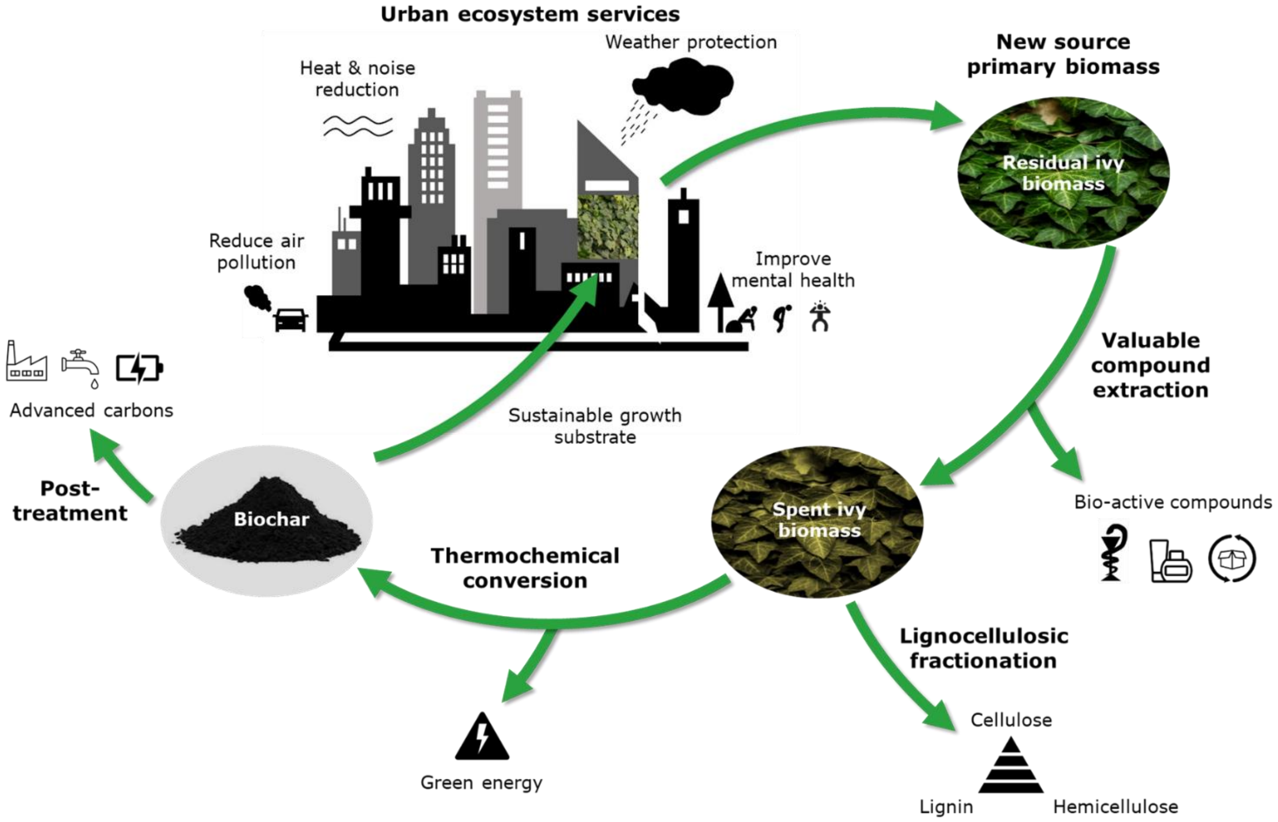

Figure 1: Common ivy in a biorefinery concept which entails the complete valorization of the biomass stream

Urban ecosystem service

CI in vertical ecosystems

Common ivy is a suitable candidate to be applied in urban greenery due to its ease of cultivation, climbing characteristics, and fast growth. Urban ecosystems consist mainly of two components: green roofs and vertical greenery. Vertical greenery is an overarching term consisting of living walls and green facades, Figure 2[5]. Both of these could be suitable for CI. However, green facades require fewer maintenance costs and should therefore be the preferred choice for ivy-based vertical greenery systems. There is a distinction between direct and indirect green facades. In the direct approach, plants will creep and grow on the building’s outer walls, using their roots for support. Indirect growth is guided by wires or frames, aimed to cover the whole building's exterior walls. This can be done either modular (modular trellis) or continuous (continuous guides). Contrary to green facades, living walls are specialized frames consisting of either modular or continuous series of planter tiles, flexible bags, trays, or vessels. When applied continuously, this is done by lightweight screens, on which the plants can be cultivated without directly contacting the building’s envelope[22]. CI will typically be used in direct green facades where their adventitious roots can settle directly into the building envelope. Nevertheless, initial tests in modular living walls are reported[23].

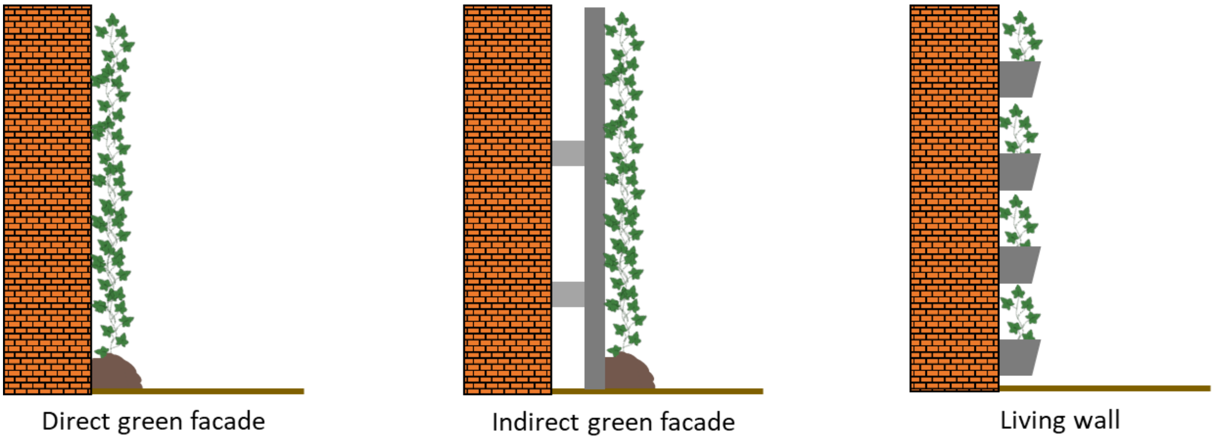

Figure 2: Vertical greenery systems suitable for common ivy, adapted from Besir et al.[5]

To assist in choosing the most suitable vertical greenery system for CI, insight into the aerial root's climbing strategy is indispensable. The first foundation was laid in 1865 when Charles Darwin observed the secretion of a yellowy sticky liquid from the root surface of climbing plants[24]. In 2008, Zhang et al. used atomic force microscopy to study this secreted substance further[25], they observed the exudation of nanoparticles between affiliated disks from the aerial rootlets of CI. These nanoparticles allow the CI to climb a surface using weak adhesion and hydrogen bonding. This secretion of nanoparticles is also the basis of the adhesion systems of other organic live forms, e.g., marine mussels. Both organisms use the exudated nanoparticles as building blocks to increase surface adhesion. However, it must be noted that their respective nanoparticles vary from a chemical point of view[26]. To understand the adhesion mechanics of CI nanoparticles, Wu et al.[27] used three different contact and fracture mechanics models and concluded that Van der Waals forces supply the major fraction of the adhesion strength of CI nanoparticles. The capillary force had a smaller contribution, which was confirmed by Xia et al.[28]. The general CI attachment process during growth can be subdivided into four main stages[29]. The first stage comprises the initial contact of the ivy attachment roots with the climbing substrate. Secondly, the attachment root system structurally adapts to fit the substrate structure and topology. This leads to an increase in the contact area between roots and substrate while also increasing root diameter and lignin content. The next stage is defined by the roots chemically adhering to the substrate surface, using the secreted nanoparticles between the root hairs. Lastly, the root hairs will change shape due to the loss of water, and form-closure with the substrate will occur. To confirm this process in real-time, Lenaghan et al.[30] visualized the secretion of adhesives by atomic force microscopy. It was concluded that the root hairs secreted the adhesive before contacting the substrate surface. Furthermore, the moment that a root tip contacts the climbing substrate serves as a signal to induce several effects: The formation of new adventitious roots above the previous one (thus explaining the climbing behavior) and morphologically changing the root itself. Huang et al. dug deeper into the role of the nanoparticles in the adhesion process, and they discovered that the particles were mainly composed of arabinogalactan proteins[31].

Vertical plant growth affects the structural integrity of buildings. CI has a double role in influencing a building's structure during plant growth. On the one hand, it deteriorates by intruding the structure's outer surface with its adventitious roots[32]. On the other hand, the ivy canopy provides both an insulating and cooling effect during winter and summer, respectively[14,15]. This protects buildings from frost damage, particulate matter deposition, and heavy rainfall. To prevent building damage, CI should be applied in indirect modular LW instead of GF, to maintain the advantages of the canopy without damaging structural integrity of the building.

Common ivy's effect on the urban heat island effect and building's energy efficiency

Surface and air temperatures in cities are higher compared to rural areas. This urban heat island effect causes an increase in citizen mortality during heat waves[4]. The application of CI in vertical ecosystems would decrease the urban heat island effect[6,7] by improving the energy retention of the adorned buildings, acting as an extra layer of isolation. Cameron et al.[33] quantified these effects by implementing an ivy canopy at different periods of the year, Figure 3A. During the first winter, energy savings were 21%. When the CI canopy density increased the second winter, energy consumption decreased by 37% compared to the reference situation without ivy. The highest energy savings can be made when facades are exposed to extreme weather (cold, wind, rain). In that case, increases in energy efficiency of up to 50% could be observed, which corresponded with exterior wall surface temperatures rising by 3 °C[33].

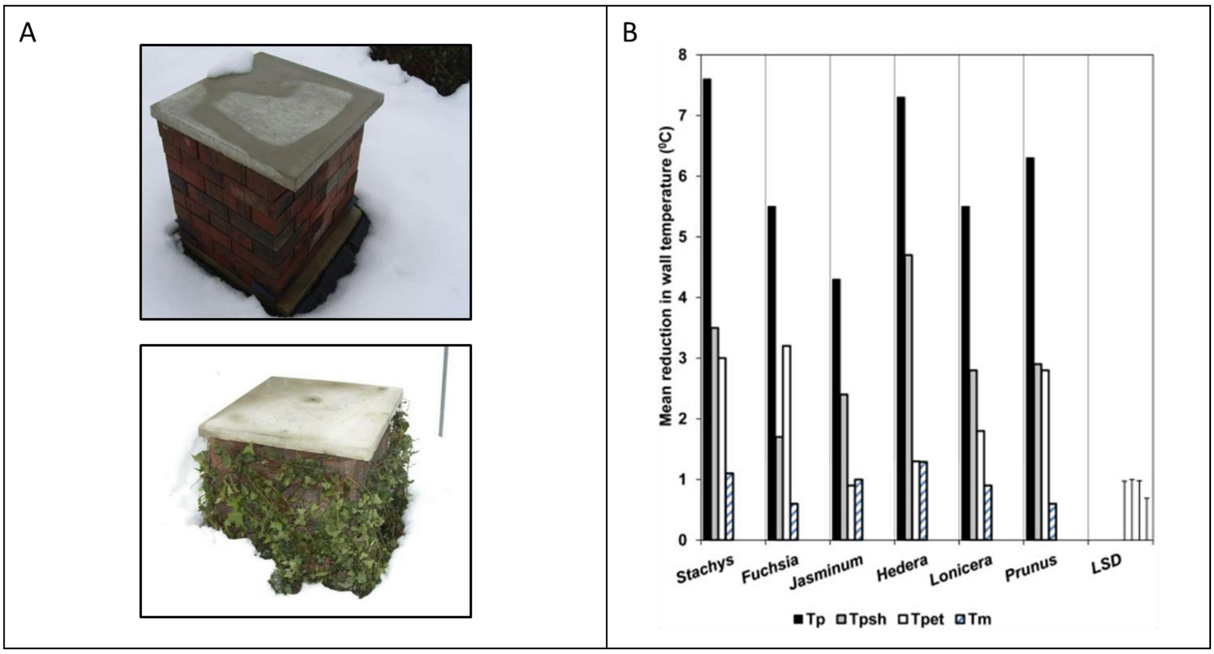

Figure 3: A) Application of common ivy on a brick cubicle (bottom) to assess the extent of energy savings compared to the bare brick (top)[33], B) Comparison of different taxa for their application in green facades to reduce the urban heat island effect[34]. Reproduced with permission of [34]. Copyright 2014 Elsevier. Reprinted with permission under a Creative Commons CC BY 4.0 from [33]. Copyright 2015 Elsevier. (Tp: Total reduction in wall temperature, Tpsh: T reduction due to shading, Tpet: T reduction due to plant evapotranspiration, Tm: T reduction due to evaporation of water by growth medium, LSD: least significant difference)

Next to energy savings in winter, vertical greenery also provides cooling during hot summers, this way (partially) offsetting the urban heat island effect. When comparing CI with other candidates for green facades, e.g., *Prunus laurocerasus*, *Jasminum officinale*, *Stachys byzantina*, *Fuchsia* 'Lady Boothby', and *Lonicera* 'Gold Flame'. Only *Stachys byzantina* was able to reach cooling comparable to CI. Their fast growth rate and early canopy densities explained the improved cooling efficiencies. The most considerable reduction in mean wall temperature (Tp) was caused by shading effects (Tpsh); plant evapotranspiration (Tpet) and evaporation of growth medium were less impactful (Tm), Figure 3B[34]. Hoelscher et al.[35] performed outdoor experiments on building facades in Berlin, Germany. There, a temperature decrease of 15.5 °C was detected on the greened exterior walls when compared with bare walls. For the interior wall, differences were around 1.7 °C, measured at night. The main driver for this cooling effect during the day was shading. At night, increased insulation was responsible for the temperature variations. Similar observations were made by Bolton et al.[36]. During a 36-day period in late winter 2012, they discovered that a cover of CI reduced external wall temperature variations. At night, a temperature increase of 1.4 °C was observed, while a decrease of 1.7 °C was detected during the day. This would make the building around 8% more energy efficient, especially on cold days. Another relevant study by Pichlhöfer et al. determined that the heat transfer of masonry walls was up to 30% lower when ivy greening was applied on the bare outer wall, moreover similar findings regarding decreased outer wall temperature in summer and incerased temperature in winter were found[37]. This proves that applying CI as vertical greenery positively affects the net energy consumption in cities during cold periods, while simultaneously decreasing the urban heat island effect in summer.

Outdoor particular matter (PM) adsorption

Outdoor air pollution is responsible for 5 - 10% of premature deaths in the United States, thereby resolving this environmental issue would be beneficial both from the healthcare and economic point of view[38]. Furthermore, the emitted $PM_{2.5}$ affect large areas of land, in 2018, the effect of $PM_{2.5}$ on cross-state premature mortality in the United States was three times that of NO_x or SO_2[39]. Moreover, long-term exposure to low concentrations of PM2.5, NO_x and carbon black was found to be associated with different types of mortality in a large-scale European study invoving 28 million people[40]. One solution for reducing air pollution and improving urban atmospheres would be vertical greenery systems, and, as stated before, CI would be an excellent candidate to be applied in these.

Common ivy is an efficient absorber of aerosols (PM_{10} and $PM_{2.5}$) in urban environments, acting as PM-sinks. He et al.[8] demonstrated that CI could effectively capture PM_{10} and $PM_{2.5}$ when applied as urban vegetation in Hannover, Germany. The leaf surface PM capturing capacity was 0.15 ± 0.04 mg/cm^2 and 0.14 ± 0.04 mg/cm^2 for PM_{10} and $PM_{2.5}$. Compared to other plant species (12 species tested in total), this was moderately high. For PM_{10} capturing capacity, only one other plant, *Berberis thunbergii*, performed significantly better. For $PM_{2.5}$, none of the other plant species had a substantially higher PM capturing capacity than CI[8]. Sternberg et al.[9] confirmed the effectiveness of CI acting as a ‘particle sink’ by PM-capture on historic walls while simultaneously preventing the bio-deterioration of these walls. Moreover, a recent investigation by Marins et al.[41] demonstrated that CI has an average specific daily removal of 94.47 mg/m^2 of PM_8. A study was conducted by Dzierzanowski et al.[42] to assess the adsorption of PM_{100}, PM_{10}, and $PM_{2.5}$ on CI and other urban vegetation and study the underlying adsorption mechanism. They investigated whether the PM was deposited on the leaf surface or trapped in its waxes. Compared to the other investigated taxa, CI captured the largest quantity of PM_{100} on its leaf surface. Inversely it trapped the smallest amount of PM_{100} in its wax layer between leaf structures, partly due to ivy containing the least amount of waxes of the studied taxa. CI was ranked 5th (of 9) in the deposition of PM_{10} aerosols. Similarly to $PM_{100,}$ their wax trapping ability was lowest, equal with *Platanus × hispanica*. For the finest fraction ($PM_{2.5}$), CI adsorbed the smallest quantity of particles of the studied taxa. Weerakkody et al.[43] studied the removal of PM_1, $PM_{2.5,}$ and PM_{10} by seventeen different plant taxa applied as vertical greenery in living walls in Birmingham. CI was adequate in removing fine particulate matter and ranked fifth (of 16) in removal per unit of surface area of the tested taxa. The captured PM was subjected to elemental analysis; it was found that the largest fractions of the PM were Fe, Ca, K, Si, Mg and Cl, also traces of Al, Ba, Cu, Na, P and S were detected. The speciation of captured PM was similar for all reported taxa, the main differences in total PM adsorption capacity was dependent on size of the PM rather than chemical speciation. The PM density on the leaves was in a greater part due to the adaxial surface of the leaves compared to the abaxial surface. It was proposed that this was due to the epicuticular wax layer present on the adaxial surface of the CI leaves. It was concluded that the smaller the particles the larger the quantities captured. This is in clear contrast with the earlier mentioned conclusions of Dzierzanowski et al.[42], where larger particles were captured to a greater extent by CI. However, it is important to note that both studies quantified the amount of adsorbed PM differently. Dzierzanowski et al.[42] did this gravimetrically, while Weerakkody et al.[43] used an Environmental Scanning Electron Microscope to visualize the leaf surfaces and count the amount of adsorbed PM. This raises the question of which methodology is more accurate to quantify the deposition of particulate matter on vertical greenery. Another study by Ottelé et al.[44] found that smaller particles were adsorbed in larger amounts than bigger ones, with the highest peaks found in the range of 0.2-4 µm. Particles larger than 10 µm were scarcely found. This was in line with the findings of Weerakoddy et al.[43], however, a comparative study between both approaches, gravimetric or environmental scaning microscopy is still non-existent, to the best of our knowledge. Zanoletti et al. compared the removal of PM_{10} and $PM_{2.5}$ by their porous material, SUNSPACE, with CI as a reference. It was concluded that SUNSPACE removed more particles. Nevertheless, CI significantly reduced the amount of PM_{10} and $PM_{2.5}$ derived from a burning candle[45]. Furthermore, CI can also trap heavy metals (which are also part of the PM fractions) on its leaves from the atmosphere, as proven by a Pb^{210} tracer method. In total, 10% of the present Pb was attributed to direct deposition from the atmosphere. Soil uptake provided the other part of the total Pb content in the plant[46].

Next to the theoretical assessment of the amount of deposition or adsorption of pollutants per leaf area of CI, an investigation in a London public school was carried out to assess the effect of different air pollution mitigation strategies on the school's air quality. This entailed, among others, the application of a CI green screen along the playground's fence. This study observed a 40, 42 and 44% reduction for PM_{10}, $PM_{2.5}$, and PM_1 at the outside monitoring station located on the school grounds[47]. This case study demonstrates the potential that ivy-based vertical greenery systems can improve the health of children.

Indoor pollutant adsorption

The previous section demonstrated the large potential of CI as the principal component of PM capturing living walls. Moreover, CI could also be used indoors as an ornamental plant to purify the air in homes, offices or public buildings. In this regard, Lin et al. studied the removal of formaldehyde (the most abundant volatile organic compound originating from household equipment) by potted CI. In this case, the time required to remove 1 ppm of formaldehyde decreased by 70% compared to natural dissipation[13]. Furthermore, Aydogan et al.[48] showed that CI could remove two-thirds of the amount of formaldehyde, around 2 mg/m^3, in a closed room within 56 min of initial exposure. Jin et al.[49] determined that the formaldehyde removal rate of CI was 2.22 mg/(m^2 h). Both studies compared the removal efficiencies with other common household plants (e.g., *Melissa officinalis*[49] or *Chrysanthemum morifolium*[48]) and concluded that CI's removal efficiency was the lowest of the studied taxa. Therefore, CI would not be the preferred choice for formaldehyde removal. Nevertheless, indoor removal of 5 other indoor pollutants (octane, benzene, toluene, trichloroethylene and α-pinene) by 28 different plant taxa, among them CI, was studied by Yang et al.[50]. In this case, CI showed the highest pollutant removal (together with 3 other species) of all tested specimen. Another study showed that potted CI reduced the concentrations of different volatile organic carbons (VOCs) (3-methylhexane, toluene, ethylbenzene, and m,p-xylenes) originating from gasoline with 16.7-22.6%. However, when epigeous plant parts were removed, the reduction increased. From this observation, it could be concluded that a large part of the reduction of VOCs can be allotted to an increased diffusion in the soil microcosm[51] and not to adsorption on the plant surface. A follow-up study demonstrated changes in the soil microcosm due to the exposure of gasoline VOCs[52]. Using NanoSIMS, Tartivel et al. proved that CI could trap bromotoluene on its leaves and roots[53]. The removal of indoor carbon dioxide by potted CI was also studied, but an unrealistically high amount of plants would be required to enhance indoor air quality significantly[54]. The potential of CI as an indoor air purifier exists, as it is very effective in removing some pollutants (octane, benzene, toluene, trichloroethylene, α-pinene, and bromotoluene), but less suitable for removing others (formaldehyde). Moreover, the growing medium used to cultivate the plants also has positive benefits on the adsorption of VOCs. Therefore, it can be concluded that there would be some merit in utilizing CI as biological air purifier, but other plant taxa showed more potential in this regard.

Physicochemical properties of CI biomass

Common ivy: a persistent evergreen vine

Hedera Helix L., is part of the ginseng family, *Araliaceae*. It can be found around the northern hemisphere (Europe, North and Central Asia, and the Americas) and blossoms in late winter or early spring. In fall, the plant carries round-clustered flowers of a greenish-yellow color. During winter, dark purple or black fruits will develop. Leaves can have a range of different shapes, depending on the age and flower-bearing capabilities of the branches. Possibilities are: laceolate, ovate, five-lobed, tri-lobed or ovate-rhomboid[55]. Other widely occurring Hedera species are *H. colchica*, Persian ivy, *H. algeriensis*, Algerian ivy, and *H. hibernica* or Atlantic ivy[56].

A distinction is made between CI's juvenile and adult forms. The juvenile form, a woody vine, consists of creeping stems that contain roots with adventitious rootlets at leaf nodes. These rootlets can develop into true roots, gaining the ability to adsorb food and water. They range from 1 to 30 cm in length and are located at nodes, along the internodes, and around 5-10 cm from the apical meristem. They have a climbing growth pattern. During this climbing process, they secrete a nanocomposite, which can be harvested and used in other applications[57]. Adult stems do not climb and have a purple-green-like appearance. The leaf shape of adult and juvenile branches is distinctly different. Adult leaves are unlobed and have an ovate to rhombic shape. While juvenile leaves are lobed (3-5 lobes), with the terminal lobe being the most prominent, basal lobes can be reduced or absent. Leaves of climbing stems are also more wedge-shaped[58]. Furthermore, adult leaves are more freezing-resistant than juvenile leaves. However, their photosynthetic capacity decreases during winter. In spring, adult leaves considerably improve their photosynthetic capacity while retaining their frost-retention capability[59].

In some instances, the presence of CI can be undesirable. It is an invasive species in the United States (US), originally imported from Europe and Asia. In the US, it acts as a suppressor for native plant species and should be removed. In the Pacific Northwest, 83% of the present ivy vines were from the species *H. hibernica* and not *H. helix* variety[60]. Biggerstaf et al. discovered that manual removal is very effective in halting invasive species proliferation, but also very labor-intensive[61]. Therefore, Yang et al.[62] investigated six different herbicides to control CI. Metsulfuron proved the most effective with more than 97% control when applied at 0.168 kg ai/ha (ai: active ingredient), by which the application of this herbicide also prevented regrowth[62]. One reason that makes CI an efficient invasive species is the presence of endophytic microbes that enhance plant survival and growth. Soares et al.[63] isolated and identified these bacteria as *Bacillus amyloliquefaciens*. Greenhouse plant experiments proved the bacteria's efficacy after exposure of inoculated and non-inoculated plants to a necrotrophic pathogen. Problems with invasive CI are expected to increase due to rising atmospheric CO_2 levels, as CI benefits more from these conditions than their tree hosts[64]. Therefore, future CI management policies have to be established. Recently, advanced remote sensing technologies (a combination of hyperspectral imaging and LiDAR mapping) were used to identify the distribution of CI in urban areas[65]. This could be a promising methodology to assist future urban planning strategies. Earlier, it was mentioned that manual removal was an effective but very labor-intensive (i.e., expensive) method. An economic incentive to remove this plant species would be needed to justify this removal methodology. Next to ivy trimmings, removing the invasive CI biomass would generate a second, ivy-biomass stream, which could be integrated into the bio-refinery process stream for the production of high-value bioproducts. This could serve as the necessary economic incentive for labor-intensive CI collection.

Composition of common ivy biomass

Common ivy has a macro-compositional structure of mostly cellulose, hemicellulose, and lignin. Furthermore, they contain significant quantities of nitrogen. Leaf nitrogen of CI ranges from 3.2 – 3.8%, independent of environmental changes (improved warming and illumination)[66]. Vercruysse et al.[21,67] thoroughly studied the elemental composition of a mixture of leaves and stems of raw CI, their results are presented in Table 1. They confirmed the high (1.8%) N content of the CI samples. Moreover, CI contains a large (48%) fraction of carbon, accumulated during the plant's growth, which showcases their large carbon sequestration potential. Lastly, CI has a high quantity of ash (4.9%, most importantly Ca and K[67], Table 1) which partially accumulates on the plant's leaf surface as PM. The carbohydrate analysis of CI was performed using a modified (additional ethanol extraction to remove interfering extractives) Van Soest & Wine fibre analysis[68]. This showed that 20% of CI was ethanol extractable (e.g., waxes, fats, saponins). Minor quantities (8%) of hemicellulose were detected, while cellulose was the most abundant lignocellulosic component (34%). Additionally, a relatively high quantitiy of acid detergent lignin was identifeied (23%), an in-depth discussion on the implications of this compostion is provided in a later section. Lastly, around 10% of CI was not identified these could include other extractives which were non-extractable by ethanol. Our data corresponds with other previously reported values for fiber (44%, mainly hemicellulose and cellulose) and lignin (17%) contents of CI[69].

Table 1: Elemental composition of CI (N, C, H, O and Ash-contents calculated as averages from previously reported data[21, 67], inorganic nutrient composition from Vercruysse et al. [67], lignocellulosic composition analysis based on Van Soest fiber analysis[68] performed on the batch studied by Vercruysse et al.[65], unpublished data)

Property (wt%, dry basis)	CI
N	1.8 ± 0.6
C	48 ± 3
H	6.3 ± 0.1
O	41 ± 2
Ash	4.9 ± 0.8
Ca	0.95 ± 0.01
K	0.78 ± 0.01
P	0.12 ± 0.02
Mg	0.12 ± 0.01
S	0.10 ± 0.01
Ethanol extractable (%)	20 ± 1
Hemicellulose (%)	8 ± 1
Cellulose (%)	35 ± 1
Lignin (%)	23 ± 2
Undetermined (%)	10 ± 1

Furthermore, CI also contains a large number of phytochemical compounds, especially in its leaves, of which the most abundant for each class of compounds are depicted in Figure 4. Lutsenko et al.[16] summarized all pharmaceutically interesting compounds in CI leaves and fruits. Leaf compounds were categorized into the following classes: triterpene saponins, flavonoids, coumarins, polyacetylenes, phenolic acids, anthocyanin, sterols, alkaloids, volatile oils, amino acids, vitamins, and carbohydrates. The fruits contained the following groups of pharmaceutical compounds: triterpene saponins, fatty acids, polyacetylenes and β-acetylenes[16]. In general, the triterpene saponins (comprise 2.5-6% of the leaves[16]) are the most important bioactive compounds. In this group, hederacoside C (1.7-4.8%) is the largest fraction Moreover, Bezruk et al.[70] did a complete phytogeographical profiling of different ivy leaf samples collected all over Southern and central-eastern Europe. It was determined that the predominant phenolic acids were 3,5-di-caffeoylquinic acid and chlorogenic acid. For the flavonoid compounds, the most abundant were hyperoside and apigenin-7-glucoside. Alanine and proline were the most abundant amino acids. Ultimately, the triterpene saponins were present in the order, from most to least abundant, of hederacoside C (1.7-4.8%) > hederacoside D (0.4-0.8%) > α-hederin (0.1-0.3%) > hederasaponin B (0.1-0.2%)[70]. In a subsequent study, variations in phytogeographical profile were correlated with environmental factors (duration of sunshine, soil type, climate, altitude and precipitation). Negative correlations between duration of sunshine and climate were found with the amount of phytochemicals, which was evident from CI originating from northern countries (Poland, Lithuania) containing more phytochemicals than CI derived from southern countries (Italy, Greece). For hederacoside C, variations between northern and southern countries ranged from 49.63 – 109.46 compared to 13.54 – 33.79 mg/g, respectively. Furthermore, the total phytochemical content in CI was maximized when cultivated in luvisol[71]. It can be concluded that CI contains large quantities of valuable phytochemicals and to maximize their content, the ivy should be cultivated in northern countries. This way, the ivy-based biorefinery system would generate a larger quantity of high-value extracts whose extraction entails the next step in the proposed system.

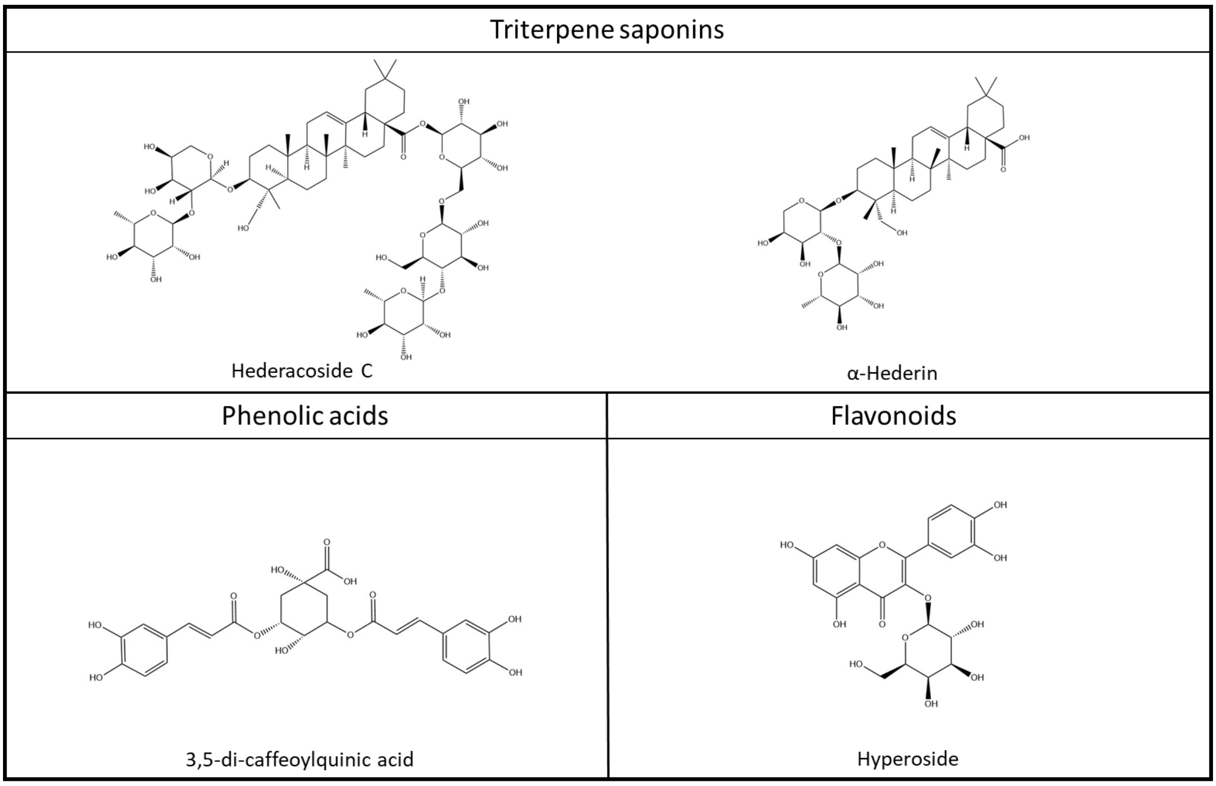

Figure 4: Chemical structures of common ivy-derived phytochemical compounds as determined by Bezruk et al.[70], chemical structures adopted from Chemspider[72]

Common ivy extractives and their application

Preparation and composition

CI leaf extracts are prepared commercially using an ethanolic solution (30-70%, depending on the manufacturer). Engelhard Arzneimittel GmbH & Co. KG (Germany) (producer of Prospan®) owns a U.S. patent (US 7,943,184 B2) for producing an ethanolic (30%) extract of CI which contains a considerable amount of hederacoside C and α-hederin[73]. One of the critical parameters for efficient extraction is the biomass particle size. It directly impacted the polyphenolic content and anti-oxidant effect of the resulting extracts (70% ethanol). Powder particle size between 100-350 µm delivered the highest polyphenol content and associated anti-oxidant effects. Particle sizes exceeding 500 µm and unsieved powders gave the lowest recoveries of polyphenolics[74]. Therefore, the ivy extraction system requires a grinding step before extraction. Commercial CI extraction systems still use large quantities of organic solvents which require large amounts of energy for their use and recovery. Therefore, novel extraction methodologies are being researched extensively. As an example, Gavrila et al. proposed an ultrasound-assisted extraction methodology to obtain saponins from ivy leaves, this way less energy would be used during the extraction process. The optimal extraction protocol used 80% ethanol, 60 min extraction time at 50 °C, an ultrasound amplitude of 40% which corresponds to 27.9 W, and a 1:20 plant:solvent ratio (w:v)[75]. After the extraction of the phytochemicals, quantification is necessary to assure the quality of the produced extracts.

The quantification of the extracted active components (saponins and flavonoids) from CI is done by reverse phase high-performance liquid chromatography (RP-HPLC) using a gradient elution scheme coupled with a diode array detector (DAD)[55,76,77] or regular UV-VIS detector[78]. Hàvlikova et al. decreased analysis time from 30 to 5 min per ethanolic extract by adjusting the elution gradient[79]. Another quantification method, ultra-performance liquid chromatography-electrospray ionization-tandem mass spectrometry (UPLC-ESI-MS/MS), has proven to be more rapid , selective and sensitive than HPLC-DAD in determining the active components in ethanolic ivy leaf cough syrups[80]. Moreover, ultra-high performance liquid chromatography-quadrupole time-of-flight-tandem mass spectrometry (UHPLC-Q-TOF-MS/MS) has also proven to be an adequate analysis methodology to quantify ivy saponins rapidly. Furthermore, this methodology allowed the identification of novel ivy-derived phytochemicals[81]. The previous shows that the quantification of CI-derived phytochemicals is not straightforward and it requires the use of highly-specialized machinery with highly-trained personell to ensure accurate identification and quantification.

CI could contain other bio-active compounds which are not efficiently extracted with aqueous ethanol or other alcohols. However, to date, no in-depth investigations have been conducted in this regard. Therefore, to expand the applicability of CI trimmings, a microwave-assisted extraction with hexane/isopropanol was performed on CI trimmings. Hereafter, samples were analyzed using one-dimensional gas chromatography coupled to mass spectroscopy (1D-GC-MS) and comprehensive two-dimensional gas chromatography coupled to mass spectroscopy (2D-GC-MS), a detailed overview of the used experimental methodology and the measured chromatograms are added in supplementary material (Appendix 1). The 2D-GC-analysis, Table 2, revealed that the CI extract contained large quantities or $C_{15}H_{24}$ sesquiterpenes (24.85% relative surface area) and $C_{15}H_{24}O$ sesquiterpenoids (20.19%). The former consisted mainly of β-copaene (12.69%), germacrene D (3.38%), γ-elemene (2.48%), valencene (2.47%), and α-copaene (2.17%). For the sesquiterpenoids these were lemnalol (2.01%), germacra-4(15),5,10(14)-triene-1-α-ol

(1.30%), salvialenone (0.95%) and isospathulenol (0.71%). 1D-GC-MS analysis identified a smaller relative quantity of sesquiterpenes compared to 2D-GC-MS. For $C_{15}H_{24}$ only 8% (compared to 24.85% for 2D-GC-MS) of the peaks were identified as such, Table 3. The identified compounds were germacrene D (6.74%), germacrene B (0.62%), and (E)-β-famesene (0.64%). For the $C_{15}H_{24}O$ sesquiterpenoids the total identified relative peak area equals only 2.51% (compared to the 20.19% for 2D-GC-MS). The identified compounds were germacra-4(15),5,10(14)-triene-1-α-ol (1.01%), isospathulenol (0.83%) and salvialenone (0.67%). The increased resolving power of the 2D-GC-MS was mainly due to an existing overlap between the sesquiterpenes and their corresponding alkanes. Overall, the previous demonstrates the strength of a 2D-GC-MS analysis for identifying biochemical compounds from herbal extracts. Moreover, the presence of sesquiterpenes in CI trimmings broadens the application potential of the biomass waste stream, as these compounds are applicable in the pharmaceutical, cosmetics, and food sector[82].

Table 2: Identified compounds of the 2D-GC-MS analysis of the hexane/isopropanol CI extract

Group No.	Group	Area %
1	C9-C10 alkane	3.96
2	C11-C12 alkane	4.37
3	C13-C14 alkane	1.03
4	C15-C16 alkane	4.16
5	C17-C18 alkane	6.32
6	C19-C20 alkane	5.68
7	C21-C25 alkane	12.10
8	C26-C29 alkane	6.28
9	C6 peroxide	0.30
10	C15H24 sesquiterpenes	24.89
11	C15H24O sesquiterpenes	20.23
12	C17-21 fatty alcohol, acid, ester	2.83
13	C26-29 fatty aldehyde	1.63
14	Di-tert-butylphenol	1.09
15	N-butyl-benzenesulfonamide	1.62
	Total from groups	96.49
Peak no.	**Ungrouped compounds**	**Area %**
34	Benzene, 1,3-bis(1,1-dimethylethyl)-	0.16
37	2,4,6-Octatriene, 2,6-dimethyl-	0.04
38	Cyclohexene, 1-methyl-4-(1-methylethylidene)-	0.06
39	Copaene	0.03
41	Cyclohexane, 1-ethenyl-1-methyl-2-(1-methylethenyl)-4-(1-methylethylidene)-	0.06
42	Methyl 8,9-octadecadienoate	0.07
43	(-)-β-Bourbonene	0.04
44	Longifolene	0.44
95	2-((2R,4aR,8aS)-4a-Methyl-8-methylenedecahydronaphthalen-2-yl)prop-2-en-1-ol	0.04
96	Andrographolide	0.11
105	13-cis-Retinal	0.04
143	2-Butenal, 2-methyl-4-(2,6,6-trimethyl-1-cyclohexen-1-yl)-	0.03
177	Cyclooctatin	0.04
266	2-Pentadecanone, 6,10,14-trimethyl-	0.07
306	Solstitialin A	0.07
309	5,8,11-Eicosatriynoic acid, methyl ester	0.10
318	Doconexent	0.02

441	9-Octadecenamide, (Z)-	0.10
507	Acetoxy-3-hydroxy-3-isopropyl-dimethyl--octahydroazulen-4-yl-methoxybenzoate	0.28
510	Squalene	0.22
517	Acetic acid, chloro-, octadecyl ester	0.15
520	Eicosane	0.06
521	Tetracosane	0.06
525	Stigmasterol	0.08
529	Cyclopentadecanol	0.18
530	Lupeol	0.07
	Total ungrouped compounds	2.62
	Total identified 2D GC-MS	99.11

Table 3: Identified compounds of the 1D-GC-MS analysis of the hexane/isopropanol CI extract

Peak No.	Compounds	Area %
1	Ethanone, 1-(3-ethyloxiranyl)-	0.22
4	Octanal	0.13
6	Nonanal	0.06
7	Octanoic acid	0.05
8	Ethanol, 2-(2-butoxyethoxy)-	0.05
9	2,4-Decadienal	0.14
10	2,4-Decadienal	0.16
11	Tetradecane	0.80
12	(E)-ß-Famesene	0.64
14	Dodecane, 4,6-dimethyl-	0.45
15	Germacrene D	6.74
17	2,4-Di-tert-butylphenol	0.51
22	Germacrene B	0.62
23	(1R,7S,E)-7-Isopropyl-4,10-dimethylenecyclodec-5-enol	0.58
24	Hexadecane	1.38
25	Salvial-4(14)-en-1-one	0.67
26	(1R,7S,E)-7-Isopropyl-4,10-dimethylenecyclodec-5-enol	1.01
27	Isospathulenol	0.83
28	.tau.-Cadinol	0.91
29	Aromadendrene oxide-(2)	0.31
30	(1R,7S,E)-7-Isopropyl-4,10-dimethylenecyclodec-5-enol	0.28
31	(1R,7S,E)-7-Isopropyl-4,10-dimethylenecyclodec-5-enol	0.27
33	(1R,7S,E)-7-Isopropyl-4,10-dimethylenecyclodec-5-enol	1.21
34	(1R,7S,E)-7-Isopropyl-4,10-dimethylenecyclodec-5-enol	0.35
35	(1R,7S,E)-7-Isopropyl-4,10-dimethylenecyclodec-5-enol	1.06
37	trans-Z-a-Bisabolene epoxide	0.60
40	(1R,7S,E)-7-Isopropyl-4,10-dimethylenecyclodec-5-enol	0.57
41	Aromadendrene oxide-(1)	0.27
42	Isospathulenol	0.41
43	Benzenesulfonamide, N-butyl-	4.17
44	Octadecane	0.58
46	Neophytadiene	0.26
47	2-Pentadecanone, 6,10,14-trimethyl-	0.30
49	Aromadendrene oxide-(2)	0.70

54	n-Hexadecanoic acid	2.70
56	Eicosane	0.28
57	Panaxynone	0.40
58	Octadecanal	0.23
59	(S,Z)-Heptadeca-1,9-dien-4,6-diyn-3-ol	5.81
60	Octadecyl octyl ether	0.50
61	9,12-Octadecadienoic acid (Z,Z)-, methyl ester	1.26
62	10-Heptadecen-8-ynoic acid, methyl ester, (E)-	1.00
63	Phytol	1.60
65	10(E),12(Z)-Conjugated linoleic acid	3.75
66	9,12,15-Octadecatrienoic acid, (Z,Z,Z)-	4.97
67	Octadecanoic acid	0.77
73	9-Octadecenamide, (Z)-	0.79
75	Pentacosane	0.69
77	Hexacosane	0.32
79	Heptacosane	1.31
82	Squalene	0.63
83	Hexacosanal	1.48
84	Nonacosane	11.54
85	d-Tocopherol	0.24
87	Octacosanal	2.17
88	Tocopherol	0.48
91	Nonacosanal	0.34
92	Triacontanal	7.78
93	Stigmasterol	2.42
96	Sitosterol	1.71
98	Lupeol	1.32
	Total identified compounds	83.81

Medical applications of common ivy extracts

Clinical effectiveness of common ivy-based pharmaceuticals

In 2017, the European Medicines Agency published a report on the medicinal use of CI leaf extract in both its liquid or solid form, stating all requirements for safe commercial use [83]. It was concluded that all requirements for commercial use are met. The provided list inicates the accepted solvent concentrations of ethanol, as well as the useable solvent to biomass ratios. The Committee on Herbal Medicine Products gave the extracts the indication of "*Herbal medicinal product used as an expectorant in case of productive cough.*". Prospective and retrospective studies with respectively 7 000 and 52 000 children ensured its safety. During pregnancy and lactation, complete safety is not confirmed within the scientific literature, as the maternal Zn distribution in rats was altered by treatment with α-hederin[83]. Furthermore, to ensure the safety of a 30% ethanolic CI leaf extract (Prospan®), Fazio et al.[84] conducted a multicentre post-marketing study on 9657 patients (5181 children). It was concluded that 95% of patients had decreased symptoms after seven days of treatment. Only mild adverse effects were reported for 2.1% of the cases, demonstrating the safety of the drug[84]. Cwientzek et al. studied the impact of two CI leaf based cough syrups (Hedelix® and Prospan®) on acute bronchitis of 590 patients. The results were similar for both extracts, indicating a daily improvement of the patient's health and a decrease in bronchitis symptoms[85]. Sierocinski et al. published a systematic review of the clinical reports regarding the use of CI-based extracts for the treatment of viral respiratory tract infections and bronchitis. It was concluded that whereas the extracts were safe for use, actual clinical effects were only minimally observed[86]. More clinical trials should be conducted to further confirm the efficacy of CI-based preparations, but, nevertheless, the current literature looks promising. An overview of the applications of common ivy-based extractives is provided in Table 4.

Common ivy extracts as an anti-inflammatory agent

Gepdiremen et al.[18] studied the anti-inflammatory effects of both α-hederin and hederacoside C and two bidesmosides (hederacolchisides E and F) derived from *H. colchica* or Persian Ivy. They concluded that hederacoside C had a significant anti-inflammatory effect, however, it was not as effective as hederacolchiside F or indomethacin (added as a positive control). Furthermore, *in vivo* and *in vitro* experiments suggest that Hederacoside C would be applicable to treat acute lung inflammation induced by the bacteria S*taphylococcus aureus*. Treatment with hederacoside C suppressed Toll-like receptors 2 and 4 and inhibited proinflammatory cytokines' production, resulting in anti-inflammatory effects[87].

Anti-carcinogenic effects of common ivy-based chemicals

Nanostructured lipid carriers derived from plant-based oils, can efficiently (up to 82% for hederacoside C) entrap the active components of a CI-leaf extract[88]. They have a free oxygen radical scavenging effect (94-98%), making them powerful anti-oxidants. Furthermore, these nanostructured lipid carriers induce apoptosis in B16 tumor cells (around 38% after a 72 h treatment), while normal L929 cell lines retain a viability of 92%. Therefore, they show high potential as effective phytochemical delivery systems in cancer therapy[88]. Furthermore, α-hederin has been shown to have antineoplastic effects for different types of cancer cells. For example, α-hederin, effectively inhibits the growth of esophageal squamous cell carcinoma in mice[19]. Similar positive effects were found for the inhibition of gastric cancer cells[89]. Apoptosis was induced in both studies by activating the mitochondrial dependent apoptotic signaling pathway. Alpha-hederin also induced cell death in lung carcinoma, larynx epidermoid carcinoma, colon adenocarcinoma and pancreas carcinoma[90]. Zhan et al. reported beneficial effects of using α-hederin in combination with paclitax to treat non-small cell lung cancer[91]. Furthermore, to improve the uptake of α-hederin by the body, chitosan-derived nanoparticles were applied as successful carriers for α-hederin, to treat liver tumors[92]. An optimal ratio between α-hederin, hederagenin and hederacoside C to instigate the maximal antiproliferative activity when applied to Hep-2 (human) epithelial cervix tumor cells was proposed by Tatia et al.[93]. Of the three components, α-hederin showed the highest antiproliferative activity with cell viabilities ranging from 0.5-51%, depending on concentration (10 – 400 µg/ml) after a treatment time of 24 h. Hederagenin lowered cell viability to 52% for 25 – 400 µg/ml. Lastly, hederacoside C did not decrease cell viability for the tested concentrations (2 – 400 µg/ml). The optimal saponin ratio was calculated to be 3.863:100.000:596.137 (wt%) for α-hederin, hederagenin, and hederacoside C, respectively. *In vitro* experiments showed that, when applied to Hep-2 epithelial cervix tumor cells, this ratio yielded a tumor viability of 35% (cultivated in minimum essential medium (MEM)) and a biocompatibility with normal mouse fibroblasts (NCTC cells) of 80% viability[93]. These *in vitro* findings were improved upon by a follow-up study, where different mixtures of α-hederin, hederagenin, and hederacoside C were tested, the best performing ratio (30:100:360 (wt%)) was better than the previously calculated ratio leading to 90% viability of NCTC cells and tumor viability of 55% (MEM supported by 10% fetal bovine serum (FBM)) compared to respectively 80 and 76% for the theoretically calculated ratio[94]. To summarize, it was proven that CI contains readily extractable components which can be very efficiently applied to treat different tumors, although more extensive animal trials are required before human trials should be commenced, as large scale experiments were not reported before.

Common ivy extracts: potential COVID-19 therapy

CI-based cough syrups have been commercially available for a long time and have shown improvements in the symptomatic treatment of bronchitis[83]. Therefore, it could potentially aid in the treatment of other bronchial ailments. In recent years, one of these diseases got a lot of attention in the scientific community due to societal relevance, i.e., COVID-19 or SARS-Cov-2. A recent publication by Silveira et al. tested herbal medicine as an adjuvant symptomatic therapy against COVID-19. Of the 39 tested herbal medicines, CI-based preparations were one out of five herbal medicines that were deemed positive regarding their benefits versus risks assessment. As Silveira et al. reported that the use of these extracts is completely safe and could have a positive suppressive effect on symptoms caused by SARS-Cov-2[95]. Another argument for the potential efficacy of CI-based extracts for the treatment of SARS-Cov-2 is based on the molecular docking of α-hederin on the main protease of COVID-19. Bouchantouf and Missoum showed that this molecular docking of α-hederin, was the most energetically favorable compared with other COVID-associated drugs (chloroquine, hydroxychloroquine, and faviparivir)[96]. However, no clinical discussion on the use of CI-based therapies for the treatment of COVID-19 has been reported yet.

Emerging medical applications of common ivy extracts

Next to the earlier mentioned anti-inflammatory, anti-carcinogenic and beneficial bronchial effects of CI-extracts, some other novel medicinal applications are under investigation. Purified CI extracts containing hederagenin and α-hederin proved to be novel autophagic inducers, through the degradation of mutant proteins, α-dyn, and huntingtin, in mice. Hence, establishing their neuro-protective capabilities, makes them interesting candidates to modulate Parkinson's and Huntington's disease[97]. Furthermore, Moshaie-Nezhad et al.

proposed that CI extracts could prevent paracetamol-induced renal damage in mice, as significant reductions in blood urea nitrogen, creatinine, and uric acid levels were observed in the kidneys of treated mice[98]. Lastly, the flavonoid fraction of the ethanolic ivy extract would be a suitable candidate for treating rheumatoid arthritis (RA). The total ivy ethanolic extract and its isolated flavonoids fraction significantly ($p\text{-value} < 0.05$) repressed the biochemical, pathological and oxidative changes in rats caused by RA. Interestingly, the saponin fraction did not have any significant effects[99].

Non-medical applications of common ivy extracts

As discussed in the previous section, CI extracts are mainly used to treat bronchial ailments. Moreover, an extensive research field exists to widen the applicability of plant-based drugs. However, a significant time discrepancy exists between the initial research into new therapies and their practical implementation. On average, this takes 10-15 years from initial discovery to regulatory approval. Therefore, it would be interesting to look into other non-medical applications of CI-extracts, whose application horizon is not as long.

Common ivy extracts' efficacy as anti-fungal agent

Emerging fungi pose a significant risk to the global food supply, therefore, novel disease control strategies should be investigated[100]. Consequently, Rosca-Casian et al.[20] researched the anti-fungal activity of a 50% ethanol CI leaf extract against 6 phytopathogenic fungi strains. Results were positive and comparable with fluconazole, a synthetic drug. This implied that the extract could be used to prevent plant-related diseases, e.g., white rot, plant wilt, or grey mold. The active compounds in this extract were rutin, quercetin, kaempherol, and stigmasterol. Other researchers discussed the anti-fungal activity of CI extracts on other foods. Significant effects were found against late blight on detached tomato leaves and downy mildew in cucumber[101]. Furthermore, Baysal and Zeller demonstrated an increased resistance of apple rootstock treated with a CI extract against fire blight[102]. No significant effects were found in the treatment of common bean anthracnose[103]. However, a 25% reduction in mycelial growth of the blight disease in potatoes was found[104]. Furthermore, CI extracts could control black rot, *in vitro* and *in vivo*, in grapevine. However, the authors noted that the saponins present in the CI extracts are water-soluble, which prevents its wide-scale applicability at this moment in time[105]. Besides the leaves, the flowers and fruits of CI also possess anti-fungal constituents (polyphenols). The fruit extract had a slightly higher anti-fungal effect than the flower extract[106]. In conclusion, CI-extracts certainly demonstrated anti-fungal activity, however further research on field-scale is necessary. Another point of investigation, would be to lower the water-solubility of the applied saponins to prevent the active compounds from being removed by rain after their application.

Nanoparticles from common ivy's rootlets

A different ivy-derived product is derived from purposely cultured CI strains, and not from its trimmings. It entails the nanoparticles secreted by the ivy rootlets, which have UV-blocking properties[30]. They are more efficient, less toxic, and easier biodegradable than the TiO_2 particles usually used in commercial sunscreen[57]. This UV-protective capability was maintained at a wide temperature range (-20 – 40 °C)[107]. However, commercial application is not yet feasible as only lab-scale cultivation experiments have been carried out[108]. Lenaghan et al.[28], found that the nanoparticles were organic (no metals present above trace levels), elemental analysis showed a C, N, and S content of 51.77, 4.72, and 0.32%, respectively. From their Fourrier-transform infra-red spectra, it was postulated that the nanoparticles mainly consisted of glycoproteins[28]. Next to the earlier mentioned application, Huang et al.[109] used the nanoparticles as nanocarriers to deliver doxorubicin (chemo-therapeutic drug) to multiple different cancer cell lines. Using CI nanoparticles loaded with doxorubicin had a higher cytotoxic effect than free doxorubicin *both in vitro and in vivo (*mice). Therefore, CI nanoparticles are versatile arabinogalactan protein-rich nanomaterials that can be functionalized according to their application.

Other applications of CI-based products

Next to all the earlier mentioned applications of ivy-derived products, some alternative uses were recently investigated. Hederacoside C and α-hederin work as potent anti-oxidants with a total anti-oxidant activity of 86 and 94%, respectively, this was comparable to reference anti-oxidants (a-tocopherol, butylated hydroxyanisole, and butylated hydroxytoluene)[17]. Abbasifar et al. used CI-extracts to synthesize silver nanoparticles (by initiating a reaction between $AgNO_3$ and the extract), which can be used in many applications. Their research focused on the antibacterial activity of the nanoparticles against two bacteria strains. They concluded that the nanoparticles had significantly higher antimicrobial activity than either the extract alone or $AgNO_3$[110]. Saponin-rich ethanolic CI extracts were also used to improve bacterial metabolism in biodegradation processes. Zdarta et al.[111] found that the extract enhanced the viability of the cells (*Acinetobacter calcoaceticus*) during the biodegradation process. However, the saponins themselves were also more efficiently degraded, i.e., used as a carbon source, which slowed down the hydrocarbon degradation[111]. Crude hydroethanolic extracts of CI fruit also had a moderate anthelmintic effect on eggs and adult nematode parasites (*Haemonchus contortus*) both *in vivo* and *in vitro*[112].

The table below summarizes the applicability of all CI-derived products (Table 4). Utilizing CI trimmings to produce these products would generate a large quantity of spent ivy, which should be processed further.

Table 4: Overview of potential applications of CI-derived products (n.d.: not determined)

Solution/form	Active Component	Application	Effectiveness	Ref.
Isolated and purified saponins from ivy leaves and fruits	Hederacoside C, α-hederin	Anti-oxidant	Total anti-oxidant activity: Hederacoside C (86%), α-hederin (94%)	17
Isolated saponins from ivy leaves	Hederacoside C, α-hederin	Anti-inflammatory agent (acute lung inflammation treatment)	Hederacoside C effective after four hours, α-hederin no signicifant effects	18
Hederacoside C	Hederacoside C	Acute bacterial lung inflammation	Suppression of TLR2 and TLR4 and production of proinflammatory cytokines	87
Ivy leaves extract (14.65% hederacoside C)	Hederacoside C	Active component entrapped by nanostructured lipid carrier for cancer treatment	Apoptosis in B16 tumor cells, 38% (72 h treatment)	88
Commercial α-hederin (≥ 90%)	α-hederin	Cancer treatment (inhibiting growth of esophageal cell carcinoma)	Significant decrease in tumor size and volume in mice	19
Commercial α-hederin (≥ 90%)	α-hederin	Cancer treatment (inhibiting growth of gastric cancer cells)	Significant decrease in tumor size and volume in mice	89
Solution of commercial α-hederin in 100% DMSO	α-hederin	Cancer treatment (inducing apoptosis in lung carcinoma, larynx epidermoid carcinoma, colon adenocarcinoma and pancreas carcinoma)	21.6% apoptosis after 24 h	90
Commercial α-hederin combined with paclitax	α-hederin	Cancer treatment (inducing apoptosis in non-small lung cancer)	Combination therapy promising treatment strategy	91
α-hederin with chitosan derived carriers	α-hederin	Cancer treatment (inducing apoptosis in liver tumors)	Nanoparticles with α-hederin effectively captured in tumor cells and affected mobility and stability	92
Mixture of α-hederin, hederacoside C, and Hederagenin	α-hederin, hederagenin	Cancer treatment (inducing apoptosis in Hep-2 epithelial cervix tumor cells)	Optimal saponin mixture determined, hederacoside C no antriproliferative effects, the others did.	93, 94
Purified CI extracts	α-hederin, hederagenin	Modulator of Parkinson's and Huntingtons disease	Extracts facilitate autophagal degradation of huntingtin and α-syn	97
CI extracts	n.d.	Prevention of paracetamol induced renal damage	Significant reduction in serum creatine, blood urea nitrogen and uric acid in blood.	98
Ethanolic (70%) ivy leaf extract and its isolated flavonoid fraction	Flavonoids	Anti-arthritic treatment	Significant reduction in a wide array of symptoms caused by rheumatoid arthritis	99
Commercial hedera helix extract	n.d.	Adjuvant symptomatic covid-19 therapy	Benefits/risks assessment shows that common-ivy based herbal medicine has potential as symptomatic therapy	95
α-hederin	α-hederin	COVID-19 treatment	Most energetically favorable drug tested	96
50% ethanol CI leaf extract	Rutin, quercetin, kaempherol, stigmasterol	Anti-fungal agent (white rot, plant wilt and grey mold)	Results comparable to synthetic drug	20
50% ethanol extract CI	n.d.	Anti-fungal agent (late blight on detached tomato leaves and downy mildew in cucumber)	Effects comparable to commercial fungicide	101
CI extract (30% ethanol)	n.d.	Anti-fungal agent (Fire blight on apple rootstock)	Significant increase in resistance to fire blight in treated apple rootstock	102
Methanolic CI extract	n.d.	Anti-fungal agent (Common bean anthracnose)	No significant effects	103
Mixed fruit and leaves extract (10% acetone)	n.d.	Anti-fungal agent (blight disease in potatoes)	25.95% reduction on the mycelial bacterial growth compared to control	104

Ethanolic extract (96% ethanol)	saponins	Anti-fungal agent (Black rot in grapevine)	Favorable effects in glasshouse experiments, not in field trials, due to saponins dissolving in water	105
Ivy fruit and flower extracts	Polyphenols and flavonoids	Anti-oxidant and antimicrobial agent	The extracts with the highest polyphenolic and flavonoid contents showed the highest effects	106
Silver nanoparticles created by reaction of $AgNO_3$ and CI extracts	n.d.	Antimicrobial activity	Larger inhibition of microbial activity by silver nanoparticles compared to AgNO3 and the CI extract	110
Saponin-rich ethanolic CI extracts	Mixture of present saponins	Biodegradation promoting agent	Positive effect on cell viability, bioavailability of compounds in extract have an adverse impact on biodegradation process	111
CI fruit extracts	n.d.	Anthelmintic effect on eggs and adult nematode parasites in sheep	Strong initial effects, long term effects not significantly proven	112
Nanoparticles secreted by ivy rootlets	Glycoprotein-like nanoparticles	Green alternative sunscreen	UV-protective capability maintained over wide temperature and pH ranges	107
Nanoparticles secreted by ivy rootlets	Glycoprotein-like nanoparticles	Nanocarrier for chemo-therapeutic drugs (doxorubicin)	Significant decrease in tumor sizes for mice treated with ivy nanoparticle-doxorubicin conjugates	109

Valorization of spent common ivy residue

The drug:extract ratio, mass ratio of the amount of plant material to the amount of obtained extract, of commercial CI extracts varies between 5-7.5:1[84], which means that 80 – 87% of the raw CI stream is discarded after extraction, even more if losses during pretreatment are accounted for. This discarded, spent, CI stream could be a promising candidate for further valorization. Keeping in mind the goals of the Paris Agreement, the proposed valorization strategy would be to sequester carbon in soils as biochar or employ it to create novel advanced carbons.

Fractionation of common ivy biomass

After ethanolic extraction of CI the lignocellulosic structure of the biomass remains largely unaffected[21]. Therefore, a next step in the valorization process could entail the fractionation of the lignocellulosic structure(s) in to each of its three main components: hemicellulose, cellulose or lignin. Each of the three is present in the biomass in different quantities as explained in Table 1. Currently, no literature is available yet which describes the fractionation of this specific biomass stream. However, as it is a herbaceous lignocellulosic biomass with a known distribution of its lignocellulosic content. An initial estimation on its applicability as a resource for different commodity chemicals and bioproducts can be made based on other comparable studies.

In terms of valorization potential after ethanolic extraction the largest remaining fractions would include cellulose (34%) and lignin (23%), hemicellulose is only present in a minor fraction (8%). Therefore, in terms of valorization potential it would be the most opportune to isolate cellulose from this feedstock as it has the largest relative quantity. Some notable applications of isolated (nano)-cellulose include food packaging, paper production, electrochemical energy storage and biosensors[113].

Isolated cellulose is one of the most important commodities as identified by the scientific community. Isolation of cellulose involves the removal of hemicellulose and lignin, this is conventionally achieved using a two-step process. The first step involves a bleaching step to remove a first fraction of lignin and waxes, pectins and tannins, commonly used bleaching agents include H_2O_2, NaOCl and $NaClO_2$. This is followed by alkaline treatment (NaOH or KOH) to remove all residual lignin and hemicellulose[114]. Current research has been searching for novel sustainable solvents for biomass fractionation as an alternative for this alkaline treatment[115]. In this regard, natural deep-eutectic solvents (NADES) show promise as sustainable recyclable biomass fractionation agents as certain NADES can dissolve lignin and hemicellulose[116]. Only one study reported the treatment of CI with NADES[65], specifically choline chloride:malic acid. In this study, it was found that the NADES could effectively remove inorganic minerals from the biomass, more over large fractions of organic matter were extracted in the process. Nevertheless, no in-depth characterization on the organic matter extraction was done in this study, hence the efficacy of this NADES as fractionator for lignocellulosic biomass remains a conjecture and further research would be necessary for confirmation.

To close the mass balance the extracted hemicellulose and lignin compounds should also be valorized further into bio-products. One of the most promising strategies for hemicellulose is by conversion into its sugar monomers via hydrolysis, which can be used as a feedstock for the production of a wide range of commodity chemicals or biofuels after further processing [117]. Residual lignin is the largest source of aromatic molecules in nature. They are notoriously difficult to purify due to its large heterogeneity, disordered structure and high intrinsic recalcitrance. Nevertheless, a lot of research has been carried out to produce novel bioproducts from residual lignin, including phenol derivatives, carbon fibers, bioplastics, activated carbons[118]. One of the promising strategies for residual lignin conversion is thermochemical conversion[119] as a means to produce solid bioproducts, i.e., biochar and activated carbons.

Valorization of common ivy residues via slow pyrolysis

Thermochemical conversion (pyrolysis) is one of the most investigated strategies to fractionate biomass into different valuable products. By heating the biomass under inert atmosphere it is fractionated into a gas, liquid and solid phase[120]. These gas and liquid phases can be used to produce biofuels. However, the produced gaseous and liquid compounds are generally very heterogenous and large efforts into their upgrading is needed to create consumer quality bio-oils from biomass[121]. Nevertheless, the simplicity, wide range of applicability and robustness of the technique makes it a suitable technique for biomass fractionation. Next to the gas and liquid-phases also a solid phase is produced, biochar.

Biochar is the solid residue of biomass slow pyrolysis, when its production is favored, the gas and oil phases are viewed as residue streams and converted into bioenergy in the form of heat to provide the intrinsic energy requirements, which results in a carbon-negative production process[120]. Moreover, biochar has several beneficial properties (high amounts of nutrients, increased water retention, improved soil carbon content, …) that promote plant growth and therefore increase their applicability as green fertilizers[122]. Other comparable biomass streams have been successfully converted into well-functioning biochars, e.g., barley grass[123], mallee leaf[124] and bamboo[125]. Recently, Vercruysse et al.[21] investigated the application of raw and spent CI biomass streams as biochars. The biochars were thoroughly characterized, and the effects of pyrolysis temperature and pretreatment processes (extraction with ethanol and steam distillation) were investigated. It was concluded that extraction with ethanol and pyrolysis temperatures of 400 °C would be the most suitable for biochar fertilizer application, as the obtained products exhibited a high carbon and nitrogen content and contained a large amount of nutrients that would prove to be beneficial for plant growth. Biochars produced from steam-distilled biomass at 700 °C were more suitable for carbon sequestration, owing to their superior carbon content and biochar stability. To verify the findings of Vercruysse et al. plant growth experiments should be carried out.

Biochar is a relatively low-value product (436 - 863 EUR/ton[126]). To add value to the bio-refinery process chain, biochars could be activated, resulting in activated carbon (5000 EUR/ton values averaged from[127]). Activations can be done using either physical activating agents (steam or carbon dioxide) or chemical activating agents (KOH or $ZnCl_2$). The main goal of this activation would be to enhance the porous character of the material, typical specific surface areas range from 1000 – 2500 m^2/g for activated carbons[128]. Activated carbon applications are mainly in the field of adsorption, adsorbing pharmaceuticals[129], heavy metals[130, 131], dyes[132] or gaseous pollutants (CO_2, H_2, VOC)[133]. They can potentially serve as the primary electrode material in next-generation electronic devices, e.g., Li-ion batteries or supercapacitors. This is a green and feasible way to valorize waste biomass, as demonstrated by Mensah-Dakwa et al.[134], who listed ca. 50 different types of biowastes which have been successfully converted to activated carbon for these types of applications. Moreover, a recent study reported the creation of activated carbons from CI. In this study, the impact and sequence of various demineralization treatments (including a natural deep-eutectic solvent) on CI trimmings was investigated. It was concluded that CI was a promising feedstock for the production of activated carbons, moreover depending on the production strategy the CI-derived activated carbons would applicable as phosphate adsorbents[67].

Sustainability and feasibility of the common ivy-based bio-refinery concept

To date, no studies concerning lifecycle analysis (LCA) of the proposed CI-based value chain exist. Therefore, the carbon and energy cycles of the proposed process were estimated based on the available literature[21,84,126,135,136]. The envisaged process consists of three steps: the initial cultivation of CI in an urban environment, the extraction of valuable compounds from this ivy biomass stream, and the pyrolysis of the spent ivy residue. This biochar would be (in part) reusable as substrate or soil amendment with the added benefit of soil carbon sequestration. Table 5 presents an estimation of the carbon- and energy balances of the proposed CI production and its biorefinery process based on calculations elaborated in Appendix 2. In summary, the E-balance for urban greening was calculated based on a case study performed by Cameron et al[135], regarding the application of CI green facades on a terraced townhouse, the energy savings determined there were extrapolated towards the production of 1 ton of wet ivy trimmings. Using a conversion factor this E-balance was converted into carbon balance. The next part of the assessment started with this 1 ton of wet biomass and calculated the E and C-balances based on actual extraction and pyrolysis experiments performed on lab-scale[21] and coupled this with data from other studies[84,126,136] to obtain reliable estimates on the energy needed for the different process steps (drying, purification, pumping) as shown in Figure S2.

Table 5: Sustainability assessment of a common ivy based bio-refinery concept, calculations based on previously reported data[21]

Property	Urban greenery		Solvent extraction	Slow pyrolysis	Complete bio-refinery
	Urban heating	Common ivy cultivation			
Mass balance	/	1000 kg wet biomass	54.9 kg dry extract 278 kg dry spent ivy biomass	85.08 kg ivy biochar 192.97 kg pyro-gas	/
E-balance (kWh/ton biomass input)	-7160	0	+ 942	- 396	+ 546
C-balance ($kgCO_2eq$/ton biomass input)	- 1969	- 545	+ 259	+ 211.5	- 74

In summary, the total process (combination of urban greenery service and bio-refinery approach) is both energy and carbon negative. In one year, a CI-based green wall could save 7160 kWh of energy per ton of produced wet ivy trimming, corresponding to 1969 $kgCO_2eq$. The valorization of wet ivy trimmings in a bio-refinery process needs an external energy input of 546 kWh per ton of processed wet ivy trimmings. In this case, the bio-refinery process would be carbon-negative, removing 74 $kgCO_2eq$ per ton biomass input. In Belgium, around 2 million terraced townhouses exist[137], based on the case described in appendix 2, this would correspond to an external wall surface of $56.4 \cdot 10^6$ m^2 outer wall surface area. Hypothetically, when this complete wall area would be covered with a dense ivy canopy, this would yield 112.8 kton of wet ivy trimmings per year. In terms of energy and carbon savings (combining both urban heating savings and the bio-refinery process, which equals a total energy saving of 6614 kWh and 2043 $kgCO_2eq$ per ton of annually produced trimmings) this would result in 746 GWh and $230 \cdot 10^6$ kgCO_2eq. In practical terms, this energy saving corresponds to the annual heating of 66 000 homes in one year[138]. In conclusion, a CI-based bio-refinery process would be worth a more in-depth investigation from a sustainability point of view. Nevertheless, initial estimations prove its high potential as a sustainable resource in future biomass-based biorefineries.

Conclusions and future perspectives

This study demonstrates the potential of CI as a novel bioresource in a bio-refinery system. CI biomass would be an ideal candidate to be applied in vertical greenery systems, where it would improve the city's overall energy efficiency, reduce the urban heat island effects and improve overall urban atmospheric quality through PM-capture. Furthermore, CI biomass holds promise as a resource for the production of a wide array of bioproducts. CI extracts are already commercially applied to treat bronchial ailments, moreover, in this capacity, it has potential as a symptomatic therapy to treat COVID-19. Initial research on their efficacy as anti-cancer or anti-inflammatory agents looks promising, and other medicinal applications are currently under investigation. Non-medical applications of CI have also received attention from the scientific community, their anti-fungal properties were demonstrated in several instances. To promote the circularity of the proposed biorefinery system, research on spent ivy residues has shown its potential for carbon sequestration and soil remediation as biochar. The scientific merit of investigating CI as bioresources was even more substantiated by a first sustainability assessment which indicated that the proposed process would be beneficial in terms of energy savings and greenhouse gas reduction. In summary, CI is a biomass stream that should be investigated further to be incorporated into future green city concepts.

To reach the application phase, further research should focus on the following:

- Study on the seasonal and geographical variation of CI and their effects on the final composition of the vine should be carried out. Currently, the only reliable dataset which has reported this only described Eastern and Southern-European sampling locations[70].

- CI can adsorb PM from air, thereby purifying the atmosphere. However, this PM will be present in the resulting ivy biomass streams, therefore, the impact on the resulting biomass composition should be studied. As well as green separation methods should be investigated to separate unwanted pollutants (e.g., heavy metals) from the resulting biomass.
- Current CI extraction methodologies still rely heavily on traditional extraction solvents, the synthesis of which is highly energy-intensive. Therefore, alternative, more sustainable extraction methodologies should be investigated.
- CI trimmings show promise as a source for a wide range of bioproducts via the fractionation of its lignocellulosic structure. However, currently no research is available in this field of research, therefore we advise that this should become a major focal point for future research towards developing a zero-waste CI-based biorefinery.
- Investigations towards the application of biochar produced from spent ivy residues should be carried out, both in the framework of utilizing the biochar as green fertilizers or growth substrates within urban greening (a recent study showed promise for using biochar as additive in a green wall substrate[139]), as well as for other industrial applications, e.g., as a replacement for coal in the steelmaking industry.
- CI trimmings have the potential to be used as feedstock for advanced carbon materials, e.g., activated carbons, carbon nanodots, or hard carbon. However, this has rarely[67] been studied before and should become a major focal point in future research.
- A thorough lifecycle analysis of CI as a bioresource should be carried out, to assess the environmental impact of the proposed valorization process.

Supporting information

- Appendix 1: GC-MS and 2D-GC-MS analysis of common-ivy derived hexane:isopropanol extract
- Appendix 2: Sustainability assessment common-ivy based bio-refinery

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References

(1) United Nations. *2022 Revision of World Population Prospects* . https://population.un.org/wpp/ (accessed 2023-01-17).

(2) Raji, B.; Tenpierik, M. J.; van den Dobbelsteen, A. The Impact of Greening Systems on Building Energy Performance: A Literature Review. *Renew. Sustain. Energy Rev.* **2015**, *45*, 610–623. https://doi.org/10.1016/j.rser.2015.02.011.

(3) Zhang, X.; Chen, X.; Yue, Y.; Wang, S.; Zhao, B.; Huang, X.; Li, T.; Sun, Q.; Wang, J. Ecological Study on Global Health Effects Due to Source-Specific Ambient Fine Particulate Matter Exposure. *Cite This Environ. Sci. Technol* **2023**, *57*. https://doi.org/10.1021/acs.est.2c06752.

(4) Rizvi, S. H.; Alam, K.; Iqbal, M. J. Spatio -Temporal Variations in Urban Heat Island and Its Interaction with Heat Wave. *J. Atmos. Solar-Terrestrial Phys.* **2019**, *185*, 50–57. https://doi.org/10.1016/j.jastp.2019.02.001.

(5) Besir, A. B.; Cuce, E. Green Roofs and Facades: A Comprehensive Review. *Renew. Sustain. Energy Rev.* **2018**, *82* (October 2017), 915–939. https://doi.org/10.1016/j.rser.2017.09.106.

(6) Manoli, G.; Fatichi, S.; Schläpfer, M.; Yu, K.; Crowther, T. W.; Meili, N.; Burlando, P.; Katul, G. G.; Bou-Zeid, E. Magnitude of Urban Heat Islands Largely Explained by Climate and Population. *Nature* **2019**, *573* (7772), 55–60. https://doi.org/10.1038/s41586-019-1512-9.

(7) Wong, N. H.; Tan, C. L.; Kolokotsa, D. D.; Takebayashi, H. Greenery as a Mitigation and Adaptation Strategy to Urban Heat. *Nat. Rev. Earth Environ.* **2021**, *2* (3), 166–181. https://doi.org/10.1038/s43017-020-00129-5.

(8) He, C.; Qiu, K.; Pott, R. Reduction of Urban Traffic–Related Particulate Matter—Leaf Trait Matters. *Environ. Sci. Pollut. Res.* **2020**, *27* (6), 5825–5844. https://doi.org/10.1007/s11356-019-07160-0.

(9) Sternberg, T.; Viles, H.; Cathersides, A.; Edwards, M. Dust Particulate Absorption by Ivy (Hedera Helix L) on Historic Walls in Urban Environments. *Sci. Total Environ.* **2010**, *409*, 162–168. https://doi.org/10.1016/j.scitotenv.2010.09.022.

(10) Manso, M.; Teotónio, I.; Silva, C. M.; Cruz, C. O. Green Roof and Green Wall Benefits and Costs: A Review of the Quantitative Evidence. *Renew. Sustain. Energy Rev.* **2021**, *135*, 110111. https://doi.org/10.1016/j.rser.2020.110111.

(11) Wang, R.; Helbich, M.; Yao, Y.; Zhang, J.; Liu, P.; Yuan, Y.; Liu, Y. Urban Greenery and Mental Wellbeing in Adults: Cross-Sectional Mediation Analyses on Multiple Pathways across Different Greenery Measures. *Environ. Res.* **2019**, *176*, 108535. https://doi.org/10.1016/j.envres.2019.108535.

(12) Rajesh Banu, J.; Preethi; Kavitha, S.; Tyagi, V. K.; Gunasekaran, M.; Karthikeyan, O. P.; Kumar, G. Lignocellulosic Biomass Based Biorefinery: A Successful Platform towards Circular Bioeconomy. *Fuel* **2021**, *302* (March), 121086.

https://doi.org/10.1016/j.fuel.2021.121086.

(13) Lin, M.-W.; Chen, L.-Y.; Chuah, Y.-K. Investigation of A Potted Plant (Hedera Helix) with Photo-Regulation to Remove Volatile Formaldehyde for Improving Indoor Air Quality. *Aerosol Air Qual. Res.* **2017**, *17*, 2543–2554. https://doi.org/10.4209/aaqr.2017.04.0145.

(14) Coombes, M. A.; Viles, H. A.; Zhang, H. Thermal Blanketing by Ivy (Hedera Helix L.) Can Protect Building Stone from Damaging Frosts. *Sci. Rep.* **2018**, *8* (1), 9834. https://doi.org/10.1038/s41598-018-28276-2.

(15) Sternberg, T.; Viles, H.; Cathersides, A. Evaluating the Role of Ivy (Hedera Helix) in Moderating Wall Surface Microclimates and Contributing to the Bioprotection of Historic Buildings. *Build. Environ.* **2011**, *46* (2), 293–297. https://doi.org/10.1016/j.buildenv.2010.07.017.

(16) Lutsenko, Y.; Bylka, W.; Matławska, I.; Darmohray, R. Hedera Helix as a Medicinal Plant. *Herba Pol.* **2010**, *56* (1), 84–96.

(17) Gülçin, I.; Mshvildadze, V.; Gepdiremen, A.; Elias, R. Antioxidant Activity of Saponins Isolated from Ivy: α-Hederin, Hederasaponin-C, Hederacolchiside-E and Hederacolchiside-F. *Planta Med.* **2004**, *70* (6), 561–563. https://doi.org/10.1055/s-2004-827158.

(18) Gepdiremen, A.; Mshvildadze, V.; Süleyman, H.; Elias, R. Acute Anti-Inflammatory Activity of Four Saponins Isolated from Ivy: Alpha-Hederin, Hederasaponin-C, Hederacolchiside-E and Hederacolchiside-F in Carrageenan-Induced Rat Paw Edema. *Phytomedicine* **2005**, *12* (6–7), 440–444. https://doi.org/10.1016/j.phymed.2004.04.005.

(19) Wang, J.; Wu, D.; Zhang, J.; Liu, H.; Wu, J.; Dong, W. α-Hederin Induces Apoptosis of Esophageal Squamous Cell Carcinoma via an Oxidative and Mitochondrial-Dependent Pathway. *Dig. Dis. Sci.* **2019**, *64* (12), 3528–3538. https://doi.org/10.1007/s10620-019-05689-1.

(20) Roşca-Casian, O.; Mircea, C.; Vlase, L.; Gheldiu, A.-M.; Teuca, D. T.; Pârvu, M. Chemical Composition and Antifungal Activity of Hedera Helix Leaf Ethanolic Extract. *Acta Biol. Hung.* **2017**, *68* (2), 196–207. https://doi.org/10.1556/018.68.2017.2.7.

(21) Vercruysse, W.; Smeets, J.; Haeldermans, T.; Joos, B.; Hardy, A.; Samyn, P.; Yperman, J.; Vanreppelen, K.; Carleer, R.; Adriaensens, P.; Marchal, W.; Vandamme, D. Biochar from Raw and Spent Common Ivy: Impact of Preprocessing and Pyrolysis Temperature on Biochar Properties. *J. Anal. Appl. Pyrolysis* **2021**, *159*, 105294. https://doi.org/10.1016/j.jaap.2021.105294.

(22) Manso, M.; Castro-Gomes, J. Green Wall Systems: A Review of Their Characteristics. *Renew. Sustain. Energy Rev.* **2015**, *41*, 863–871. https://doi.org/10.1016/j.rser.2014.07.203.

(23) Ascione, F.; De Masi, R. F.; Mastellone, M.; Ruggiero, S.; Vanoli, G. P. Green Walls, a Critical Review: Knowledge Gaps, Design Parameters, Thermal Performances and Multi-Criteria Design Approaches. *Energies* **2020**, *13* (9), 2296.

https://doi.org/10.3390/en13092296.

(24) Darwin, C. On the Movements and Habits of Climbing Plants. *J. Linn. Soc. London* **1865**, *9*, 1–118.

(25) Zhang, M.; Liu, M.; Prest, H.; Fischer, S. Nanoparticles Secreted from Ivy Rootlets for Surface Climbing. *Nano Lett.* **2008**, *8* (5), 1277–1280. https://doi.org/10.1021/nl0725704.

(26) Zhang, M.; Liu, M.; Bewick, S.; Suo, Z. Nanoparticles to Increase Adhesive Properties of Biologically Secreted Materials for Surface Affixing. *J. Biomed. Nanotechnol.* **2009**, *5* (3), 294–299. https://doi.org/10.1166/jbn.2009.1034.

(27) Wu, Y.; Zhao, X.; Zhang, M. Adhesion Mechanics of Ivy Nanoparticles. *J. Colloid Interface Sci.* **2010**, *344* (2), 533–540. https://doi.org/10.1016/j.jcis.2009.12.041.

(28) Lenaghan, S. C.; Burris, J. N.; Chourey, K.; Huang, Y.; Xia, L.; Lady, B.; Sharma, R.; Pan, C.; LeJeune, Z.; Foister, S.; Hettich, R. L.; Stewart, C. N.; Zhang, M. Isolation and Chemical Analysis of Nanoparticles from English Ivy (Hedera Helix L.). *J. R. Soc. Interface* **2013**, *10* (87), 1–9. https://doi.org/10.1098/rsif.2013.0392.

(29) Melzer, B.; Steinbrecher, T.; Seidel, R.; Kraft, O.; Schwaiger, R.; Speck, T. The Attachment Strategy of English Ivy: A Complex Mechanism Acting on Several Hierarchical Levels. *J. R. Soc. Interface* **2010**, *7* (50), 1383–1389. https://doi.org/10.1098/rsif.2010.0140.

(30) Lenaghan, S. C.; Zhang, M. Real-Time Observation of the Secretion of a Nanocomposite Adhesive from English Ivy (Hedera Helix). *Plant Sci.* **2011**, *183*, 206–211. https://doi.org/10.1016/j.plantsci.2011.08.013.

(31) Huang, Y.; Wang, Y.; Tan, L.; Sun, L.; Petrosino, J.; Cui, M.-Z.; Hao, F.; Zhang, M. Nanospherical Arabinogalactan Proteins Are a Key Component of the High-Strength Adhesive Secreted by English Ivy. *Proc. Natl. Acad. Sci.* **2016**, *113* (23), E3193–E3202. https://doi.org/10.1073/pnas.1600406113.

(32) Bartoli, F.; Romiti, F.; Caneva, G. Aggressiveness of Hedera Helix L. Growing on Monuments: Evaluation in Roman Archaeological Sites and Guidelines for a General Methodological Approach. *Plant Biosyst.* **2017**, *151* (5), 866–877. https://doi.org/10.1080/11263504.2016.1218969.

(33) Cameron, R. W. F.; Taylor, J.; Emmett, M. A Hedera Green Façade – Energy Performance and Saving under Different Maritime-Temperate, Winter Weather Conditions. *Build. Environ.* **2015**, *92*, 111–121. https://doi.org/10.1016/j.buildenv.2015.04.011.

(34) Cameron, R. W. F.; Taylor, J. E.; Emmett, M. R. What's 'Cool' in the World of Green Façades? How Plant Choice Influences the Cooling Properties of Green Walls. *Build. Environ.* **2014**, *73*, 198–207. https://doi.org/10.1016/j.buildenv.2013.12.005.

(35) Hoelscher, M.-T.; Nehls, T.; Jänicke, B.; Wessolek, G. Quantifying Cooling Effects of Facade Greening: Shading, Transpiration and Insulation. *Energy Build.* **2016**, *114*, 283–290. https://doi.org/10.1016/j.enbuild.2015.06.047.

(36) Bolton, C.; Rahman, M. A.; Armson, D.; Ennos, A. R. Effectiveness of an Ivy Covering at Insulating a Building against the Cold in Manchester, U.K: A Preliminary Investigation. *Build. Environ.* **2014**, *80*, 32–35. https://doi.org/10.1016/j.buildenv.2014.05.020.

(37) Pichlhöfer, A.; Korjenic, A.; Sulejmanovski, A.; Streit, E. Influence of Facade Greening with Ivy on Thermal Performance of Masonry Walls. *Sustainability* **2023**, *15* (12), 9546. https://doi.org/10.3390/su15129546.

(38) Us Epa office of Policy Analysis. *The Benefits and Costs of the Clean Air Act from 1990 to 2020: Summary Report*; 2011.

(39) Dedoussi, I. C.; Eastham, S. D.; Monier, E.; Barrett, S. R. H. Premature Mortality Related to United States Cross-State Air Pollution. *Nature* **2020**, *578* (7794), 261–265. https://doi.org/10.1038/s41586-020-1983-8.

(40) Stafoggia, M.; Oftedal, B.; Chen, J.; Rodopoulou, S.; Renzi, M.; Atkinson, R. W.; Bauwelinck, M.; Klompmaker, J. O.; Mehta, A.; Vienneau, D.; Andersen, Z. J.; Bellander, T.; Brandt, J.; Cesaroni, G.; de Hoogh, K.; Fecht, D.; Gulliver, J.; Hertel, O.; Hoffmann, B.; Hvidtfeldt, U. A.; Jöckel, K. H.; Jørgensen, J. T.; Katsouyanni, K.; Ketzel, M.; Kristoffersen, D. T.; Lager, A.; Leander, K.; Liu, S.; Ljungman, P. L. S.; Nagel, G.; Pershagen, G.; Peters, A.; Raaschou-Nielsen, O.; Rizzuto, D.; Schramm, S.; Schwarze, P. E.; Severi, G.; Sigsgaard, T.; Strak, M.; van der Schouw, Y. T.; Verschuren, M.; Weinmayr, G.; Wolf, K.; Zitt, E.; Samoli, E.; Forastiere, F.; Brunekreef, B.; Hoek, G.; Janssen, N. A. H. Long-Term Exposure to Low Ambient Air Pollution Concentrations and Mortality among 28 Million People: Results from Seven Large European Cohorts within the ELAPSE Project. *Lancet Planet. Heal.* **2022**, *6* (1), e9–e18. https://doi.org/10.1016/S2542-5196(21)00277-1.

(41) Martins, M.; Hadba, L.; Mendonça, P.; Silva, L. T. Evaluating the Potential of Vegetation to Capture Pollutants in Urban Environment. *Environ. Sci. Eng.* **2022**, *2*, 3–13. https://doi.org/10.1007/978-981-19-1704-2_1/FIGURES/5.

(42) Dzierżanowski, K.; Popek, R.; Gawrońska, H.; Saebø, A.; Gawroński, S. W. Deposition of Particulate Matter of Different Size Fractions on Leaf Surfaces and in Waxes of Urban Forest Species. *Int. J. Phytoremediation* **2011**, *13* (10), 1037–1046. https://doi.org/10.1080/15226514.2011.552929.

(43) Weerakkody, U.; Dover, J. W.; Mitchell, P.; Reiling, K. Particulate Matter Pollution Capture by Leaves of Seventeen Living Wall Species with Special Reference to Rail-Traffic at a Metropolitan Station. *Urban For. Urban Green.* **2017**, *27*, 173–186. https://doi.org/10.1016/j.ufug.2017.07.005.

(44) Ottelé, M.; Van Bohemen, H. D.; Fraaij, A. L. A. Quantifying the Deposition of Particulate Matter on Climber Vegetation on Living Walls. *Ecol. Eng.* **2010**, *36*, 154–162. https://doi.org/10.1016/j.ecoleng.2009.02.007.

(45) Zanoletti, A.; Bilo, F.; Borgese, L.; Depero, L. E.; Fahimi, A.; Ponti, J.; Valsesia, A.; La Spina, R.; Montini, T.; Bontempi, E. SUNSPACE, A Porous Material to Reduce Air Particulate Matter (PM). *Front. Chem.* **2018**, *6*, 534. https://doi.org/10.3389/fchem.2018.00534.

(46) Yang, H.; Appleby, P. G. Use of Lead-210 as a Novel Tracer for Lead (Pb) Sources in

Plants. *Sci. Rep.* **2016**, *6* (1), 21707. https://doi.org/10.1038/srep21707.

(47) Abhijith, K. V.; Kukadia, V.; Kumar, P. Investigation of Air Pollution Mitigation Measures, Ventilation, and Indoor Air Quality at Three Schools in London. *Atmos. Environ.* **2022**, *289*, 119303. https://doi.org/10.1016/J.ATMOSENV.2022.119303.

(48) Aydogan, A.; Montoya, L. D. Formaldehyde Removal by Common Indoor Plant Species and Various Growing Media. *Atmos. Environ.* **2011**, *45* (16), 2675–2682. https://doi.org/10.1016/j.atmosenv.2011.02.062.

(49) Jin, C.; Zhou, X.; Zhao, H.; Liu, X.; Feng, K. Comparison of Removal of Formaldehyde Capacity Between Hedera Helix and Melissa Officinalis. *Asian J. Chem.* **2013**, *25* (7), 3823–3826. https://doi.org/10.14233/ajchem.2013.13802.

(50) Yang, D. S.; Pennisi, S. V; Son, K. C.; Kays, S. J. Screening Indoor Plants for Volatile Organic Pollutant Removal Efficienc. *HortScience* **2009**, *44* (5), 1377–1381. https://doi.org/10.1166/asl.2017.10363.

(51) Dela Cruz, M.; Tomasi, G.; Müller, R.; Christensen, J. H. Removal of Volatile Gasoline Compounds by Indoor Potted Plants Studied by Pixel-Based Fingerprinting Analysis. *Chemosphere* **2019**, *221*, 226–234. https://doi.org/10.1016/j.chemosphere.2018.12.125.

(52) Dela Cruz, M.; Svenningsen, N. B.; Nybroe, O.; Müller, R.; Christensen, J. H. Removal of a Complex VOC Mixture by Potted Plants—Effects on Soil Microorganisms. *Environ. Sci. Pollut. Res.* **2023**, *30* (19), 55372–55381. https://doi.org/10.1007/s11356-023-26137-8.

(53) Tartivel, R.; Tatin, R.; Delhaye, T.; Maupas, A.; Gendron, A.; Gautier, S.; Lavastre, O. Visualization and Localization of Bromotoluene Distribution in Hedera Helix Using NanoSIMS. *Chemosphere* **2012**, *89* (7), 805–809. https://doi.org/10.1016/j.chemosphere.2012.04.058.

(54) Gubb, C.; Blanusa, T.; Griffiths, A.; Pfrang, C. Interaction between Plant Species and Substrate Type in the Removal of CO2 Indoors. *Air Qual. Atmos. Heal.* **2019**, *12* (10), 1197–1206. https://doi.org/10.1007/s11869-019-00736-2.

(55) Demirci, B.; Goppel, M.; Demirci, F.; Franz, G. HPLC Profiling and Quantification of Active Principles in Leaves of Hedera Helix L. *Pharmazie* **2004**, *59* (10), 770–774.

(56) Stace, C. A. *New Flora of the British Isles*, Third.; Cambridge University Press: Cambridge, 2010, 1-1232.

(57) Xia, L.; Lenaghan, S. C.; Zhang, M.; Zhang, Z.; Li, Q. Naturally Occurring Nanoparticles from English Ivy: An Alternative to Metal-Based Nanoparticles for UV Protection. *J. Nanobiotechnology* **2010**, *8* (1), 12. https://doi.org/10.1186/1477-3155-8-12.

(58) Strelau, M.; Clements, D. R.; Benner, J.; Prasad, R. The Biology of Canadian Weeds: 157. Hedera Helix L. and Hedera Hibernica (G. Kirchn.) Bean. *Can. J. Plant Sci.* **2018**, *98* (5), 1005–1022. https://doi.org/10.1139/cjps-2018-0009.

(59) Rehm, E. M.; Lenz, A.; Hoch, G.; Körner, C. Spring Patterns of Freezing Resistance and Photosynthesis of Two Leaf Phenotypes of Hedera Helix. *Basic Appl. Ecol.* **2014**, *15* (6),

543–550. https://doi.org/10.1016/j.baae.2014.07.009.

(60) Clarke, M. M.; Reichard, S. H.; Hamilton, C. W. Prevalence of Different Horticultural Taxa of Ivy (Hederaspp., Araliaceae) in Invading Populations. *Biol. Invasions* **2006**, *8* (2), 149–157. https://doi.org/10.1007/s10530-004-2424-6.

(61) Biggerstaff, M. S.; Beck, C. W. Effects of Method of English Ivy Removal and Seed Addition on Regeneration of Vegetation in a Southeastern Piedmont Forest. *Am. Midl. Nat.* **2007**, *158* (1), 206–220. https://doi.org/10.1674/0003-0031.

(62) Yang, Q.; Wehtje, G.; Gilliam, C. H.; McElroy, J. S.; Sibley, J. L. English Ivy (Hedera Helix) Control with Postemergence-Applied Herbicides. *Invasive Plant Sci. Manag.* **2013**, *6* (3), 411–415. https://doi.org/10.1614/IPSM-D-13-00009.1.

(63) Soares, M. A.; Li, H.-Y.; Bergen, M.; da Silva, J. M.; Kowalski, K. P.; White, J. F. Functional Role of an Endophytic Bacillus Amyloliquefaciens in Enhancing Growth and Disease Protection of Invasive English Ivy (Hedera Helix L.). *Plant Soil* **2016**, *405* (1–2), 107–123. https://doi.org/10.1007/s11104-015-2638-7.

(64) Manzanedo, R. D.; Ballesteros-Cánovas, J.; Schenk, F.; Stoffel, M.; Fischer, M.; Allan, E. Increase in CO $_2$ Concentration Could Alter the Response of *Hedera Helix* to Climate Change. *Ecol. Evol.* **2018**, *8* (16), 8598–8606. https://doi.org/10.1002/ece3.4388.

(65) Chance, C. M.; Coops, N. C.; Plowright, A. A.; Tooke, T. R.; Christen, A.; Aven, N. Invasive Shrub Mapping in an Urban Environment from Hyperspectral and LiDAR-Derived Attributes. *Front. Plant Sci.* **2016**, *7* (OCTOBER2016), 1528. https://doi.org/10.3389/FPLS.2016.01528/BIBTEX.

(66) Blondeel, H.; Remy, E.; Perring, M. P.; Landuyt, D.; Bodé, S.; De Frenne, P.; Boeckx, P.; Verheyen, K. Larger Direct than Indirect Effects of Multiple Environmental Changes on Leaf Nitrogen of Forest Herbs. *Plant Soil* **2019**, *445* (1–2), 199–216. https://doi.org/10.1007/s11104-019-04298-1.

(67) Grizzetti, B.; Pretato, U.; Lassaletta, L.; Billen, G.; Garnier, J. The Contribution of Food Waste to Global and European Nitrogen Pollution. *Environ. Sci. Policy* **2013**, *33*, 186–195. https://doi.org/10.1016/J.ENVSCI.2013.05.013.

(68) Van Soest, P. J.; Wine, R. H.; Husbandry, A.; División, R. *Determination of Lignin and Cellulose in Acid-Detergent Fiber with Permanganate*; 1968; Vol. 51.

(69) Metcalfe, D. J. Hedera Helix L. *J. Ecol.* **2005**, *93* (3), 632–648. https://doi.org/10.1111/j.1365-2745.2005.01021.x.

(70) Bezruk, I.; Marksa, M.; Georgiyants, V.; Ivanauskas, L.; Raudone, L. Phytogeographical Profiling of Ivy Leaf (Hedera Helix L.). *Ind. Crops Prod.* **2020**, *154*, 112713. https://doi.org/10.1016/j.indcrop.2020.112713.

(71) Bezruk, I.; Materiienko, A.; Gubar, S.; Proskurina, K.; Budanova, L.; Ivanauskas, L.; Georgiyants, V. Estimation of the Influence of the Environmental Factors on the Accumulation of Phytochemicals and Antioxidant Capacity in the Ivy Leaves (Hedera Helix L.). *Nat. Prod. Res.* **2020**, 1–6. https://doi.org/10.1080/14786419.2020.1843029.

(72) Royal Society of Chemistry: ChemSpider. *CSID: 9666711, 660366, 23220982, 444962*.

www.chemspider.com (accessed 2023-01-23).

(73) Runkel, F.; Schneider, W.; Schmidt, O.; Engelhard, G. M. United States Patent: Process for Preparing an Extract from Ivy Leaves, 2011. https://doi.org/10.1038/incomms1464.

(74) Zaiter, A.; Becker, L.; Baudelaire, E.; Dicko, A. Optimum Polyphenol and Triterpene Contents of Hedera Helix (L.) and Scrophularia Nodosa (L.): The Role of Powder Particle Size. *Microchem. J.* **2018**, *137*, 168–173. https://doi.org/10.1016/j.microc.2017.10.011.

(75) Gavrila, A. I.; Tatia, R.; Seciu-Grama, A.-M.; Tarcomnicu, I.; Negrea, C.; Calinescu, I.; Zalaru, C.; Moldovan, L.; Raiciu, A. D.; Popa, I. Ultrasound Assisted Extraction of Saponins from Hedera Helix L. and an In Vitro Biocompatibility Evaluation of the Extracts. *Pharmaceuticals* **2022**, *15* (10), 1197. https://doi.org/10.3390/ph15101197.

(76) Khdair, A.; Mohammad, M. K.; Tawaha, K.; Al-Hamarsheh, E.; AlKhatib, H. S.; Al-khalidi, B.; Bustanji, Y.; Najjar, S.; Hudaib, M. A Validated RP HPLC-PAD Method for the Determination of Hederacoside C in Ivy-Thyme Cough Syrup. *Int. J. Anal. Chem.* **2010**, *2010*, 1–5. https://doi.org/10.1155/2010/478143.

(77) Yu, M.; Shin, Y. J.; Kim, N.; Yoo, G.; Park, S. J.; Kim, S. H. Determination of Saponins and Flavonoids in Ivy Leaf Extracts Using HPLC-DAD. *J. Chromatogr. Sci.* **2015**, *53* (4), 478–483. https://doi.org/10.1093/chromsci/bmu068.

(78) Yasmeen, S.; Yasmeen, S.; Khattak, S. U. R.; Navead, S.; Almas, Y.; Saquib, N. U.; Sadia, H.; Qamar, F.; Sana, A.; Aman, T.; Khan, M. U. Quantification of Triterpene Saponins of Hedera Helix Spray-Dried Extract by HPLC. *J. Hunan Univ. Nat. Sci.* **2022**, *49* (9), 17–23. https://doi.org/10.55463/issn.1674-2974.49.9.3.

(79) Havlíková, L.; Macáková, K.; Opletal, L.; Solich, P. Rapid Determination of α-Hederin and Hederacoside C in Extracts of Hedera Helix Leaves Available in the Czech Republic and Poland. *Nat. Prod. Commun.* **2015**, *15* (9), 1529–1531.

(80) Kim, N.; Shin, Y. J.; Park, S.; Yoo, G.; Kim, Y.; Yoo, H. H.; Kim, S. H. Simultaneous Determination of Six Compounds in Hedera Helix L. Using UPLC-ESI–MS/MS. *Chromatographia* **2017**, *80* (7), 1025–1033. https://doi.org/10.1007/s10337-017-3317-z.

(81) Pham, H. N.; Tran, C. A.; Trinh, T. D.; Nguyen Thi, N. L.; Tran Phan, H. N.; Le, V. N.; Le, N. H.; Phung, V. T. UHPLC-Q-TOF-MS/MS Dereplication to Identify Chemical Constituents of Hedera Helix Leaves in Vietnam. *J. Anal. Methods Chem.* **2022**, *2022*, 1–18. https://doi.org/10.1155/2022/1167265.

(82) Mischko, W.; Hirte, M.; Fuchs, M.; Mehlmer, N.; Brück, T. B. Identification of Sesquiterpene Synthases from the Basidiomycota Coniophora Puteana for the Efficient and Highly Selective β-Copaene and Cubebol Production in E. Coli. *Microb. Cell Fact.* **2018**, *17* (1), 164. https://doi.org/10.1186/s12934-018-1010-z.

(83) European Medicines Agency - Committee on Herbal Medicinal Products (HMPC). *Assessment Report on Hedera Helix L., Folium*; 2017. https://doi.org/10.1103/PhysRevE.87.021001.

(84) Fazio, S.; Pouso, J.; Dolinsky, D.; Fernandez, A.; Hernandez, M.; Clavier, G.; Hecker, M.; Mexico Avenida, C. D.; Julio con calle Arismendi, de; La Cruz Estado Anzoátegui, P. Tolerance, Safety and Efficacy of Hedera Helix 1 Extract in Inflammatory Bronchial Diseases under Clinical Practice Conditions: A Prospective, Open, Multicentre Postmarketing Study in 9657 Patients. *Phytomedicine* **2009**, *16*, 17–24. https://doi.org/10.1016/j.phymed.2006.05.003.

(85) Cwientzek, U.; Ottillinger, B.; Arenberger, P. Acute Bronchitis Therapy with Ivy Leaves Extracts in a Two-Arm Study. A Double-Blind, Randomised Study vs. an Other Ivy Leaves Extract. *Phytomedicine* **2011**, *18* (13), 1105–1109. https://doi.org/10.1016/j.phymed.2011.06.014.

(86) Sierocinski, E.; Holzinger, F.; Chenot, J.-F. Ivy Leaf (Hedera Helix) for Acute Upper Respiratory Tract Infections: An Updated Systematic Review. *Eur. J. Clin. Pharmacol.* **2021**, *77* (8), 1113–1122. https://doi.org/10.1007/s00228-021-03090-4.

(87) Akhtar, M.; Shaukat, A.; Zahoor, A.; Chen, Y.; Wang, Y.; Yang, M.; Umar, T.; Guo, M.; Deng, G. Anti-Inflammatory Effects of Hederacoside-C on Staphylococcus Aureus Induced Inflammation via TLRs and Their Downstream Signal Pathway in Vivo and in Vitro. *Microb. Pathog.* **2019**, *137*, 103767. https://doi.org/10.1016/j.micpath.2019.103767.

(88) Lacatusu, I.; Badea, N.; Badea, G.; Brasoveanu, L.; Stan, R.; Ott, C.; Oprea, O.; Meghea, A. Ivy Leaves Extract Based – Lipid Nanocarriers and Their Bioefficacy on Antioxidant and Antitumor Activities. *RSC Adv.* **2016**, *6* (81), 77243–77255. https://doi.org/10.1039/C6RA12016D.

(89) Wang, J.; Deng, H.; Zhang, J.; Wu, D.; Li, J.; Ma, J.; Dong, W. A-Hederin Induces the Apoptosis of Gastric Cancer Cells Accompanied by Glutathione Decrement and Reactive Oxygen Species Generation via Activating Mitochondrial Dependent Pathway. *Phyther. Res.* **2020**, *34* (3), 601–611. https://doi.org/10.1002/ptr.6548.

(90) Rooney, S.; Ryan, M. F. Modes of Action of Alpha-Hederin and Thymoquinone, Active Constituents of Nigella Sativa, against HEp-2 Cancer Cells. *Anticancer Res.* **2005**, *25* (6 B), 4255–4259.

(91) Zhan, Y.; Wang, K.; Li, Q.; Zou, Y.; Chen, B.; Gong, Q.; Ho, H. I.; Yin, T.; Zhang, F.; Lu, Y.; Wu, W.; Zhang, Y.; Tan, Y.; Du, B.; Liu, X.; Xiao, J. The Novel Autophagy Inhibitor Alpha-Hederin Promoted Paclitaxel Cytotoxicity by Increasing Reactive Oxygen Species Accumulation in Non-Small Cell Lung Cancer Cells. *Int. J. Mol. Sci.* **2018**, *19* (10), 3221. https://doi.org/10.3390/ijms19103221.

(92) Zhu, R.; Zhang, C.; Liu, Y.; Yuan, Z.-Q.; Chen, W.-L.; Yang, S.-D.; Li, J.-Z.; Zhu, W.-J.; Zhou, X.-F.; You, B.-G.; Zhang, X.-N. CD147 Monoclonal Antibody Mediated by Chitosan Nanoparticles Loaded with α-Hederin Enhances Antineoplastic Activity and Cellular Uptake in Liver Cancer Cells. *Sci. Rep.* **2016**, *5* (1), 17904. https://doi.org/10.1038/srep17904.

(93) Tatia, R.; Zalaru, C.; Craciunescu, O.; Moldovan, L.; Oancea, A.; Calinescu, I. Optimization of Triterpene Saponins Mixture with Antiproliferative Activity. *Appl. Sci.* **2019**, *9* (23), 5160. https://doi.org/10.3390/app9235160.

(94) Tatia, R.; Tarcomnicu, I.; Moldovan, Z.; Raiciu, A. D.; Moldovan, L.; Zalaru, C. M. In Vitro Antiproliferative Activity of Triterpenoid Saponins from Leaves of Hedera Helix L. Grown in Romania. *South African J. Bot.* **2023**, *158*, 1–7. https://doi.org/10.1016/j.sajb.2023.04.018.

(95) Silveira, D.; Prieto-Garcia, J. M.; Boylan, F.; Estrada, O.; Fonseca-Bazzo, Y. M.; Jamal, C. M.; Magalhães, P. O.; Pereira, E. O.; Tomczyk, M.; Heinrich, M. COVID-19: Is There Evidence for the Use of Herbal Medicines as Adjuvant Symptomatic Therapy? *Front. Pharmacol.* **2020**, *11*, 1–44. https://doi.org/10.3389/fphar.2020.581840.

(96) Salim, B.; Noureddine, M. Identification of Compounds from Nigella Sativa as New Potential Inhibitors of 2019 Novel Coronasvirus (Covid-19): Molecular Docking Study. *ChemRxiv* **2020**, *19*, 1–12.

(97) Wu, A.-G.; Zeng, W.; Kam-Wai Wong, V.; Zhu, Y.-Z.; Lo, A. C.; Liu, L.; Yuen-Kwan Law, B. Hederagenin And-Hederin Promote Degradation of Proteins in Neurodegenerative Diseases and Improve Motor Deficits in MPTP-Mice. *Pharmacol. Res.* **2017**, *115*, 25–44. https://doi.org/10.1016/j.phrs.2016.11.002.

(98) Moshaie-Nezhad, P.; Hosseini, S. M.; Yahyapour, M.; Iman, M.; Khamesipoure, A. Protective Effect of Ivy Leaf Extract on Paracetamol-Induced Oxidative Stress and Nephrotoxicity in Mice. *J. HerbMed Pharmacol.* **2019**, *8* (1), 64–68. https://doi.org/10.15171/jhp.2019.11.

(99) Shokry, A. A.; El-Shiekh, R. A.; Kamel, G.; Bakr, A. F.; Sabry, D.; Ramadan, A. Anti-Arthritic Activity of the Flavonoids Fraction of Ivy Leaves (Hedera Helix L.) Standardized Extract in Adjuvant Induced Arthritis Model in Rats in Relation to Its Metabolite Profile Using LC/MS. *Biomed. Pharmacother.* **2022**, *145*, 112456. https://doi.org/10.1016/J.BIOPHA.2021.112456.

(100) Alothman, R. A. T.; Abdin, A. R.; Mahmoud, A. H. The Effect of Using Vegetated Façades on CO 2 Emissions in Multistory Residential Buildings, in Cold Semiarid and Hot Arid Climate. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1113* (1), 012020. https://doi.org/10.1088/1755-1315/1113/1/012020.

(101) Röhner, E.; Carabet, A.; Buchenauer, H. Effectiveness of Plant Extracts of Paeonia Suffruticosa and Hedera Helix against Diseases Caused by Phytophthora Infestans in Tomato and Pseudoperonospora Cubensis in Cucumber. *Pflanzenschutz / J. Plant Dis. Prot.* **2004**, *111* (1), 83–95.

(102) Baysal, Ö.; Zeller, W. Extract of Hedera Helix Induces Resistance on Apple Rootstock M26 Similar to Acibenzolar-S-Methyl against Fire Blight (Erwinia Amylovora). *Physiol. Mol. Plant Pathol.* **2004**, *65* (6), 305–315. https://doi.org/10.1016/j.pmpp.2005.03.003.

(103) Andrade Pinto, J. M.; Souza, E. A.; Oliveira, D. F. Use of Plant Extracts in the Control of Common Bean Anthracnose. *Crop Prot.* **2010**, *29* (8), 838–842. https://doi.org/10.1016/j.cropro.2010.03.006.

(104) Yanar, Y.; Gouml kccedil e, A.; Kadioglu, I.; Ccedil am, H.; Whalon, M. In Vitro Antifungal Evaluation of Various Plant Extracts against Early Blight Disease (Alternaria Solani) of Potato. *African J. Biotechnol.* **2011**, *10* (42), 8291–8295.

https://doi.org/10.5897/ajb11.241.

(105) Koch, E.; Enders, M.; Ullrich, C.; Molitor, D.; Berkelmann-Löhnertz, B. Effect of Primula Root and Other Plant Extracts on Infection Structure Formation of Phyllosticta Ampelicida (Asexual Stage of Guignardia Bidwellii) and on Black Rot Disease of Grapevine in the Greenhouse. *J. Plant Dis. Prot.* **2013**, *120* (1), 26–33. https://doi.org/10.1007/BF03356450.

(106) Pârvu, M.; Vlase, L.; Pârvu, A. E.; Rosca-Casian, O.; Gheldiu, A. M.; Pârvu, O. Phenolic Compounds and Antifungal Activity of Hedera Helix L. (Ivy) Flowers and Fruits. *Not. Bot. Horti Agrobot. Cluj-Napoca* **2015**, *43* (1), 53–58. https://doi.org/10.15835/nbha4319644.

(107) Huang, Y.; Lenaghan, S. C.; Xia, L.; Burris, J. N.; Stewart, C. N.; Zhang, M. Characterization of Physicochemical Properties of Ivy Nanoparticles for Cosmetic Application. *J. Nanobiotechnology* **2013**, *11* (1), 3. https://doi.org/10.1186/1477-3155-11-3.

(108) Burris, J. N.; Lenaghan, S. C.; Zhang, M.; Stewart, C. N. Nanoparticle Biofabrication Using English Ivy (Hedera Helix). *J. Nanobiotechnology* **2012**, *10* (1), 1–7. https://doi.org/10.1186/1477-3155-10-41.

(109) Huang, Y.; Wang, Y.-J.; Wang, Y.; Yi, S.; Fan, Z.; Sun, L.; Lin, D.; Anreddy, N.; Zhu, H.; Schmidt, M.; Chen, Z.-S.; Zhang, M. Exploring Naturally Occurring Ivy Nanoparticles as an Alternative Biomaterial. *Acta Biomater.* **2015**, *25*, 268–283. https://doi.org/10.1016/j.actbio.2015.07.035.

(110) Abbasifar, A.; Ghani, S.; Irvani, M. A.; Rafiee, B.; Kaji, B. V.; Akbari, A. Antibacterial Activity of Silver Nanoparticles Synthesized by Using Extracts of Hedera Helix. **2017**, *19* (1), 1–6. https://doi.org/10.17795/zjrms-5920.Research.

(111) Zdarta, A.; Smułek, W.; Pacholak, A.; Kaczorek, E. Environmental Aspects of the Use of Hedera Helix Extract in Bioremediation Process. *Microorganisms* **2019**, *7* (2), 43. https://doi.org/10.3390/microorganisms7020043.

(112) Eguale, T.; Tilahun, G.; Debella, A.; Feleke, A.; Makonnen, E. Haemonchus Contortus: In Vitro and in Vivo Anthelmintic Activity of Aqueous and Hydro-Alcoholic Extracts of Hedera Helix. *Exp. Parasitol.* **2007**, *116*, 340–345. https://doi.org/10.1016/j.exppara.2007.01.019.

(113) Dhali, K.; Ghasemlou, M.; Daver, F.; Cass, P.; Adhikari, B. A Review of Nanocellulose as a New Material towards Environmental Sustainability. *Sci. Total Environ.* **2021**, *775*, 145871. https://doi.org/10.1016/j.scitotenv.2021.145871.

(114) Marakana, P. G.; Dey, A.; Saini, B. Isolation of Nanocellulose from Lignocellulosic Biomass: Synthesis, Characterization, Modification, and Potential Applications. *J. Environ. Chem. Eng.* **2021**, *9* (6), 106606. https://doi.org/10.1016/j.jece.2021.106606.

(115) Wang, C.; Yang, S.; Song, X.; Pi, Q.; Zhang, Q.; Liu, Q.; Xu, Y.; Chen, L.; Ma, L. Novel Solvent Systems for Biomass Fractionation Based on Hydrogen-Bond Interaction: A Minireview. *Adv. Sustain. Syst.* **2020**, *4* (10), 2000085. https://doi.org/10.1002/adsu.202000085.

(116) Liang, X.; Zhang, J.; Huang, Z.; Guo, Y. Sustainable Recovery and Recycling of Natural Deep Eutectic Solvent for Biomass Fractionation via Industrial Membrane-Based Technique. *Ind. Crops Prod.* **2023**, *194* (December 2022), 116351. https://doi.org/10.1016/j.indcrop.2023.116351.

(117) Ajao, O.; Marinova, M.; Savadogo, O.; Paris, J. Hemicellulose Based Integrated Forest Biorefineries: Implementation Strategies. *Ind. Crops Prod.* **2018**, *126* (July), 250–260. https://doi.org/10.1016/j.indcrop.2018.10.025.

(118) Sethupathy, S.; Murillo Morales, G.; Gao, L.; Wang, H.; Yang, B.; Jiang, J.; Sun, J.; Zhu, D. Lignin Valorization: Status, Challenges and Opportunities. *Bioresour. Technol.* **2022**, *347* (January), 126696. https://doi.org/10.1016/j.biortech.2022.126696.

(119) Liu, W. J.; Jiang, H.; Yu, H. Q. Thermochemical Conversion of Lignin to Functional Materials: A Review and Future Directions. *Green Chem.* **2015**, *17* (11), 4888–4907. https://doi.org/10.1039/c5gc01054c.

(120) Lehmann, J. A Handful of Carbon. *Nature* **2007**, *447* (7141), 143–144. https://doi.org/10.1038/447143a.

(121) Lahijani, P.; Mohammadi, M.; Mohamed, A. R.; Ismail, F.; Lee, K. T.; Amini, G. Upgrading Biomass-Derived Pyrolysis Bio-Oil to Bio-Jet Fuel through Catalytic Cracking and Hydrodeoxygenation: A Review of Recent Progress. *Energy Convers. Manag.* **2022**, *268* (May), 115956. https://doi.org/10.1016/j.enconman.2022.115956.

(122) Marmiroli, M.; Bonas, U.; Imperiale, D.; Lencioni, G.; Mussi, F.; Marmiroli, N.; Maestri, E. Structural and Functional Features of Chars From Different Biomasses as Potential Plant Amendments. *Front. Plant Sci.* **2018**, *9* (August), 1–13. https://doi.org/10.3389/fpls.2018.01119.

(123) Nan, H.; Yang, F.; Zhao, L.; Mašek, O.; Cao, X.; Xiao, Z. Interaction of Inherent Minerals with Carbon during Biomass Pyrolysis Weakens Biochar Carbon Sequestration Potential. *ACS Sustain. Chem. Eng.* **2019**, *7* (1), 1591–1599. https://doi.org/10.1021/acssuschemeng.8b05364.

(124) Gao, X.; Yani, S.; Wu, H. Pyrolysis of Spent Biomass from Mallee Leaf Steam Distillation: Biochar Properties and Recycling of Inherent Inorganic Nutrients. *Energy and Fuels* **2014**, *28* (7), 4642–4649. https://doi.org/10.1021/ef501114v.

(125) Chen, W.; Chen, Y.; Yang, H.; Xia, M.; Li, K.; Chen, X.; Chen, H. Co-Pyrolysis of Lignocellulosic Biomass and Microalgae: Products Characteristics and Interaction Effect. *Bioresour. Technol.* **2017**, *245*, 860–868. https://doi.org/10.1016/j.biortech.2017.09.022.

(126) Haeldermans, T.; Campion, L.; Kuppens, T.; Vanreppelen, K.; Cuypers, A.; Schreurs, S. A Comparative Techno-Economic Assessment of Biochar Production from Different Residue Streams Using Conventional and Microwave Pyrolysis. *Bioresour. Technol.* **2020**, *318*, 124083. https://doi.org/10.1016/j.biortech.2020.124083.

(127) Alhashimi, H. A.; Aktas, C. B. Life Cycle Environmental and Economic Performance of Biochar Compared with Activated Carbon: A Meta-Analysis. *Resour. Conserv. Recycl.* **2017**, *118*, 13–26. https://doi.org/10.1016/j.resconrec.2016.11.016.

(128) Abioye, A. M.; Ani, F. N. Recent Development in the Production of Activated Carbon Electrodes from Agricultural Waste Biomass for Supercapacitors: A Review. *Renew. Sustain. Energy Rev.* **2015**, *52*, 1282–1293. https://doi.org/10.1016/j.rser.2015.07.129.

(129) Bhadra, B. N.; Seo, P. W.; Jhung, S. H. Adsorption of Diclofenac Sodium from Water Using Oxidized Activated Carbon. *Chem. Eng. J.* **2016**, *301*, 27–34. https://doi.org/10.1016/j.cej.2016.04.143.

(130) Hernández Rodiguez, M.; Yperman, J.; Carleer, R.; Maggen, J.; Dadi, D.; Gryglewicz, G.; Van der Bruggen, B.; Falcón Hernández, J.; Otero Calvis, A. Adsorption of Ni(II) on Spent Coffee and Coffee Husk Based Activated Carbon. *J. Environ. Chem. Eng.* **2018**, *6* (1), 1161–1170. https://doi.org/10.1016/j.jece.2017.12.045.

(131) Vanderheyden, S. R. H.; Vanreppelen, K.; Yperman, J.; Carleer, R.; Schreurs, S. Chromium(VI) Removal Using in-Situ Nitrogenized Activated Carbon Prepared from Brewers' Spent Grain. *Adsorption* **2018**, *24* (2), 147–156. https://doi.org/10.1007/s10450-017-9929-7.

(132) Lam, S. S.; Liew, R. K.; Wong, Y. M.; Yek, P. N. Y.; Ma, N. L.; Lee, C. L.; Chase, H. A. Microwave-Assisted Pyrolysis with Chemical Activation, an Innovative Method to Convert Orange Peel into Activated Carbon with Improved Properties as Dye Adsorbent. *J. Clean. Prod.* **2017**, *162*, 1376–1387. https://doi.org/10.1016/J.JCLEPRO.2017.06.131.

(133) Choma, J.; Marszewski, M.; Osuchowski, L.; Jagiello, J.; Dziura, A.; Jaroniec, M. Adsorption Properties of Activated Carbons Prepared from Waste CDs and DVDs. *ACS Sustain. Chem. Eng.* **2015**, *3* (4), 733–742. https://doi.org/10.1021/acssuschemeng.5b00036.

(134) Mensah-Darkwa, K.; Zequine, C.; Kahol, P. K.; Gupta, R. K. Supercapacitor Energy Storage Device Using Biowastes: A Sustainable Approach to Green Energy. *Sustain.* **2019**, *11* (2). https://doi.org/10.3390/su11020414.

(135) Cameron, R. W. F.; Taylor, J.; Emmett, M. A Hedera Green Façade – Energy Performance and Saving under Different Maritime-Temperate, Winter Weather Conditions. *Build. Environ.* **2015**, *92*, 111–121. https://doi.org/10.1016/j.buildenv.2015.04.011.

(136) Croxatto Vega, G.; Sohn, J.; Voogt, J.; Birkved, M.; Olsen, S. I.; Nilsson, A. E. Insights from Combining Techno-Economic and Life Cycle Assessment – a Case Study of Polyphenol Extraction from Red Wine Pomace. *Resour. Conserv. Recycl.* **2021**, *167*, 105318. https://doi.org/10.1016/J.RESCONREC.2020.105318.

(137) Attia, S.; Canonge, T.; Popineau, M.; Cuchet, M. Developing a Benchmark Model for Renovated, Nearly Zero-Energy, Terraced Dwellings. *Appl. Energy* **2022**, *306* (October 2021). https://doi.org/10.1016/j.apenergy.2021.118128.

(138) United States Environmental Protection Agency. *Greenhouse Gas Equivalencies Calculator*. https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator (accessed 2022-11-30).

(139) Costamagna, E.; Caruso, A.; Galvão, A.; Rizzo, A.; Masi, F.; Fiore, S.; Boano, F. Impact of Biochar and Graphene as Additives on the Treatment Performances of a Green Wall Fed with Greywater. *Water* **2023**, *15* (1), 195. https://doi.org/10.3390/w15010195.

(140) *Greenhouse gas emission intensity of electricity generation in Europe*. https://www.eea.europa.eu/ims/greenhouse-gas-emission-intensity-of-1 (accessed 2022-11-22).

(141) Huang, Y. F.; Lo, S. L. Predicting Heating Value of Lignocellulosic Biomass Based on Elemental Analysis. *Energy* **2020**, *191*, 116501. https://doi.org/10.1016/J.ENERGY.2019.116501.

(142) Cross, A.; Sohi, S. P. A Method for Screening the Relative Long-Term Stability of Biochar. *GCB Bioenergy* **2013**, *5* (2), 215–220. https://doi.org/10.1111/gcbb.12035.

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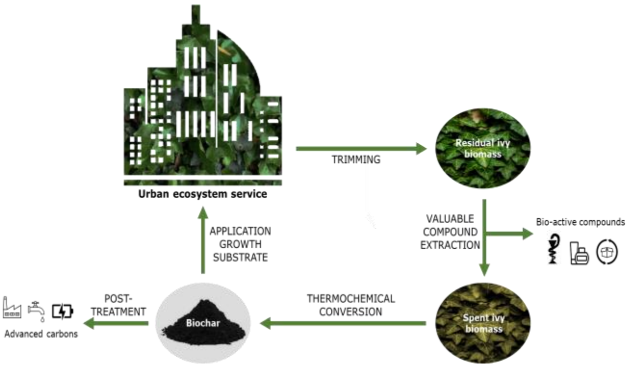

Synopsis

Common ivy biomass is a promising feedstock for pyrolysis-based urban bio-refinery processes, from urban greenery to novel bioproducts, applicable in a variety of industries.

Author biographies

Willem Vercruysse

Willem Vercruysse is currently a doctoral candidate in the research group of Analytical and Circular Chemistry at Hasselt University under the supervision of Prof. Dries Vandamme and Prof. Wouter Marchal. He started his PhD trajectory in October 2018 after finishing his Master's degree in Nuclear and Environmental Engineering. In 2019, he obtained a four-year strategic basic research grant from the Research Foundation Flanders (FWO SB - 1S92020N and FWO SB – 1S92022N). His PhD project investigates the valorization of biomass residue streams using various thermochemical conversion techniques for the creation of biochars and activated carbons which could be used for multiple future applications (soil amendment, adsorption, electrochemical energy storage).

Bernard Noppen

Bernard Noppen is a researcher at the University of Hasselt, specialized in chromatography and mass spectrometry. He started his career at the biopharmaceutical company Thrombogenics/Oxurion after graduating as M.S. in Biology at the KU Leuven in 2004. After building expertise in an extensive list of bioanalytical technologies during his 15 years in the Biochemistry and Preclinical Production and Purification departments of Oxurion, he joined the research group Analytical and Circular Chemistry at the University of Hasselt. In his current position Bernard is responsible for several chromatography-mass spectrometry techniques used to conduct research in the field of circular and green chemistry, and scientific servicing for industry partners.

Marijke Jozefczak

Dr. Marijke Jozefczak is business developer at the Centre for Environmental Sciences (CMK) and assists professor Dries Vandamme and professor Ann Cuypers in valorizing their research. She is mainly involved in the research topics of sustainable agriculture, urban agriculture, valorization of residual streams and biobased materials. She holds a PhD degree in biology from Hasselt University and during her postdoc, she contributed to the development of a multidisciplinary applied research line within the circular economy framework using biochar to improve crop production and quality on marginal land, leading to multiple applied projects and a patent application.

Michiel Huybrechts

Michiel Huybrechts is a postdoctoral researcher at the research group of professor Ann Cuypers that focusses on metal-induced oxidative stress in plants and sustainable crop production. He is mainly engaged in research related to agricultural applications for biochar and identifying valorisation opportunities. He holds a M.S. and Ph.D. degree in biology from the KU Leuven and UHasselt respectively.

Elien Derveaux

Elien Derveaux is a postdoctoral researcher at the NMR research group of professor Peter Adriaensens that focusses on advanced material characterization for energy conversion & storage, sustainability, and sensors & healthcare. She holds a M.S. degree in Biochemistry and Biotechnology from K.U. Leuven and a Ph.D. degree in Biomedical sciences from Hasselt University.

Bart Vandecasteele

Dr. Bart Vandecasteele is senior researcher in projects on circular use of growing media and biochar use in cascade, i.e., apply biochar first to reduce emissions during biomass processing and then use the biochar-enriched soil improvers for C sequestration. He was leading the Interreg2seas Horti-BlueC project on Circular Horticulture (www.horti-bluec.eu), and was convenor of the ISHS GrowingMedia2021 symposium (www.growingmedia2021.com/). He holds a M.S. and Ph.D. degree in Bioscience Engineering from Gent University.

Ann Cuypers

Ann Cuypers is full professor at Hasselt University and PI of the laboratory of Plant Abiotic Stress Signaling & Solutions (PASS$_2$) within the Centre for Environmental Sciences. After finishing her master in Biological Sciences (Plant Biochemistry and Physiology) at KULeuven (Belgium 1995), she obtained a PhD-grant (Flemish institute for scientific and technological research in industry) and performed this at Hasselt University from 1995 to 2000. She then obtained a Marie Curie Post-Doctoral Fellowship (Feb 2001- April 2002) in the lab of Prof. Christine Foyer at IACR-Rothamsted (Harpenden, UK) on molecular strategies in detoxification of reactive oxygen species. In May 2002, she started as dr. assistant in Hasselt University, research group Environmental Biology and was appointed as professor in 2007. In this period, the investigation of metal-induced oxidative challenge responses was tackled from different angles, at different biological organization levels with strong national and international collaboration.

Wouter Marchal

Prof. Dr. Wouter Marchal obtained his PhD in physical chemistry at Hasselt university in 2018 focusing on redox mechanisms in low-temperature chemical solution deposition routes for flexible electronics. After a short post-doc of almost 1 year on the optimization of inkjet printing of metal-organic decomposition inks, he became research coordinator of the chemical innovation-supporting research unit at imo-imomec, in combination with a part-time involvement as assistant professor at Hasselt university. In this function, he was the academic responsible for analytical chemistry related services, involving approximately 250 small scale research projects/ analysis requests per annum for industrial partners. In addition, his research focus shifted to advanced characterization techniques, regularly applied in a biomass valorization context. Since October 2021, Wouter Marchal started his tenure track as a 100% assistant professor in the research group analytical and circular chemistry (ACC) at UHasselt, exploring structure-composition-property relationships of advanced materials to enable a circular economy, including designed activated carbon structures and catalysts for biorefinery processes.

Dries Vandamme

Dries Vandamme is an associate professor at Hasselt University in Belgium since 01/02/23. He is a group leader in the Circular and Analytical Chemistry (ACC) lab at the Faculty of Sciences. His team is focused on chemical innovation and the development of more sustainable materials, processes and energy sources that can contribute to a CO_2-neutral or circular economy. His work is at the interface between biology, chemistry, environmental science and technology, with an emphasis on developing and applying chemical and analytical methods for (bio)materials. Throughout his academic career, he has actively built a strong global network of collaborators, e.g. from UNSW (Australia), Wageningen University (The Netherlands), NREL (USA), Arizona State University (USA), Sandia National Laboratories (USA), as evidenced by his publication record and participation in local and international consortia.