Benefits and Challenges for Decentralized Use of Biomass as Feedstock for Chemicals

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DOI: 10.1002/cite.202500043

Supporting Information available online

A systematic analysis of the decentral preconversion of lignocellulosic biomass to a chemical intermediate including technological, legal, and economic aspects is presented. A case study of levulinic acid production from 14 types of biomass shows average variations of +/− 15.5 % in yield obviously due to the properties of the raw materials. As high yield is a key for economic operation, this motivates preprocessing technologies tailored to the specific raw material. Technological, legal, and economic analyses show the prospect to establishing decentral preprocessing units. A comparison with central biorefineries demonstrates that economy of scale can be counterbalanced by cheaper feedstock cost and tailored feeding technology, which paves the way for a distributed sourcing of carbon for chemicals.

Keywords: Biomanufacturing, Biomass, Biorefinery, Feedstocks for chemicals, Levulinic acid

Received: May 05, 2025; *revised:* May 05, 2025; *accepted:* May 09, 2025

1 Introduction

Carbon is an irreplaceable feedstock for platform chemicals that are converted into a multitude of chemical products of different functionalities and properties. If net carbon emissions to the atmosphere are to be avoided, then fossil point sources will not meet the demand, making alternative carbon sources necessary. In addition to recycling of consumed material, biogenic residues could substitute the carbon demand for chemicals. Residues originate from plants, agriculture, forestry, food industry, and organic waste. Worldwide, approximately 200 billion tons of biomass waste from food and agro-based industries are generated annually [1]. In Germany, approximately half of the 15 million tons of treated organic waste per year is not utilized chemically but composted each year [2]. An additional 22 million tons per year of lignocellulosic residues are available [3], and even more than 6 million tons of recycled wood is used solely for energetic purposes [4]. For Europe, only wood residues sum up to an annual potential of 83 million tons of carbon. This is of the same order of magnitude as the current demand of the European chemical industry [5] and thus poses a considerable source of renewable carbon.

In addition to reduction of fossil carbon in industrial value chains, the utilization of biorenewable carbon can also pose an economic incentive. The Chemistry4Climate scenario from 2023 [6] suggests that increasing the use of biomass and plastic waste as raw materials for chemicals would diminish the demand for green electricity, H_2, and CO_2, and thus directly reduce the investment required to decarbonize the chemical industry. The chemical industry, however, has largely pursued the economy of scale for very efficient central processing plants. They benefit from the time-independent offer of fossil bulk chemicals and integration within chemical sites which enables selecting the most cost-effective locations and market supplies.

In contrast, biorenewable carbon is largely distributed and varies in its quality and time of availability. Obviously, this challenges a centralized production of renewable carbon, making capacity calculations more difficult. An alternative concept could be a more decentralized production of platform chemicals at the origin of biorenewables. In that sense, processes like the bioliq® process have been developed to pyrolyze biomass into "Biosyncrude" for

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shipping to a central gasification. The biomass is collected in a radius of 30 km establishing a decentral pyrolysis capacity of 200 kt/a. Although different feedstocks impact yield and capacity [7, 8], the process per se is not designed to consider the heterogeneity of the feedstock but it is an example of clever industrial scale-down. However, the improved carbon efficiency of a selective conversion [5] motivates a feedstock-centered conversion in a dedicated process environment. Such tailored conversion units would be even more modular and distributed, like envisioned with biomanufacturing [9, 10]. This, however, focuses more on high-value products than upstream feedstock integration. For biomass utilization, this would result in a scale-out of modular capacities [11].

The precise differentiation between central and decentral processing is important at this point. In this work, the decentralized mode of production thus refers to extending the value chain with a remote location in the so-called hub-and-spoke model. Thereby biomass is preconverted into a chemical intermediate, which is then transported to a central refinery for further processing (e.g., purification). While optimization of logistics already showed the benefit of having depots for biomass supply to reduce transport cost [12], such strategies have not been realized for a preconversion step of a specific biorenewable feedstock. In contrast, the central processing is realized with stick-built plants that are custom-designed and constructed on-site, with capacity determined primarily by market demand rather than by resource availability or operational flexibility [13]. Central plants are typically developed as greenfield projects, requiring full infrastructure development and focusing on centralized, large-scale production to achieve economies of scale.

In this line, current chemical processing does not account for the physical nature of biorenewable residues. They largely occur as solids and reactions take place at the solid-liquid interface in rather viscous state contrasting the very efficient gas-phase reactions established so far [14]. This particularly impacts the first conversion step of (ligno-)cellulosic residues to chemical intermediates as the solid material complicates processing. The variability and its effect on simple properties like flowability are still not well understood [15]. In addition, the effect of variability on slurry transport against pressure is more empirical than mechanistic knowledge. The challenge is thus to develop new processing strategies that accommodate the distributed nature of biorenewable carbon sources.

This contribution presents benefits and challenges of a decentralized processing unit to preprocess raw biogenic materials using robust acid hydrolysis and dehydration to levulinic acid as a case study. Fourteen different raw materials are assessed in conversion, and different solid-liquid handling technologies are reviewed. Design options are then elaborated for technological, regulative, and economic feasibility.

2 Case Study

The case study for a decentral preconversion of (ligno-) cellulosic residues into chemicals requires a robust and universal conversion concept. The well-known dehydration of sugars in acidic conditions yields levulinic acid [16] and works with different kinds of acids as catalysts to convert several types of hexoses. Levulinic acid has been ranked as one of the top 12 platform molecules in 2004 [17] and the market shows considerable growth [18]. The process has reached a high level of maturity [19] but has not been commercialized in Europe.

The process design in this work envisions a decentral biorefinery step that converts biorenewable carbon into a liquid stream containing the platform chemical close to or at the place of feedstock origin. Process engineering is used to assess feasibility and viability. This includes the process design stages of chemical engineering up to detail engineering and cost estimation, and the consultation of local authorities to assess eligibility for permission.

The design preprocesses at least 1000 t/yr of dry biomass into diluted levulinic acid for further centralized processing. The preprocessing of biomass includes four process steps (Fig. 1). The solid biomass is fed into the pressurized conversion reactor (step A). High solid loadings are favorable to increase product concentration and space-time yields. The reaction (step B) takes place at pressures of 6.5–10 bar(g), max. 14 bar(g), and temperatures between 160–180 °C for a residence time of 1 h. Sulfuric acid (~5 wt. % in liquid phase) is used as catalyst for the reaction of lignocellulose to levulinic acid with formic acid and acetic acid as byproducts. After the reaction, the medium is flashed to release pressure and recycle water and energy (step C). The bottom effluent of the flash, a suspension of solid reaction residue and liquid product, is then fed into a solid-liquid separation (step D). The liquid contains up to 10 wt % of levulinic acid, depending on the feedstock. After separation, it is further processed in a central facility to separate and purify levulinic acid and other substances (byproducts, catalyst).

The decentral process has to be designed for continuous operation, as conceptual designs of batch equipment have shown a largely increased energy consumption due to the considerable amount of time required for heating and cooling. As available energy supply in decentral locations will be limited (usually 100–150 kW for electricity in low voltage supply), a (quasi-) continuous operation is mandatory.

3 Results and Discussion

First, the results of conversion of different raw materials are discussed to analyze the effect of material properties on yield. Next, the necessary parameters for technology selection are reviewed regarding available technology. Further, legal and economic aspects of decentral processing are

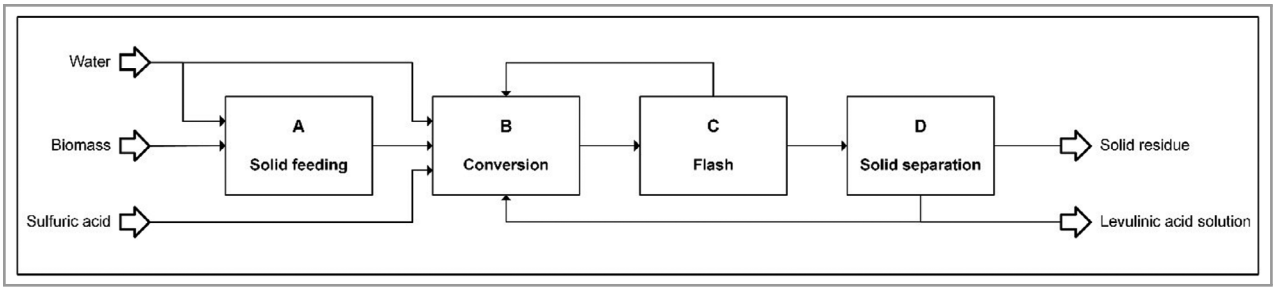

Figure 1. Block diagram of the decentral conversion concept used as case study in this work.

compared with a central design to assess the prospect of processing decentral feedstock.

3.1 Raw Materials

The conversion has been tested at 300-mL and 50-L scale with 14 different raw materials, among them wood (hardwood and softwood, waste wood), straw, wastepaper residues, rayon residues, sugar beet pellets, olive residues, and moringa press residues. The focus was on lignocellulosic raw materials as they are not in competition with food and could establish cascading use. The individual materials were selected based on local availability and cover native, lignocellulosic biomass (straw and wood residues, herbaceous plants), processed residues (pretreated and recycled biomass, industry residues), and yet underutilized food residues (olive residues). The individual yield to levulinic acid based on carbohydrate content is displayed in Fig. 2 (cf. Supporting Information (SI) for experimental details). Small chips of beech wood of 0.5–1 mm show a yield of 37 ± 4 mol. %, with comparable results at larger scale. Interestingly, chips of 6–12 mm result in higher yields at both scales. In contrast, softwood shows high yields in lab scale (50 mol. %) but dropped considerably in yield at larger scale (22 mol. %). The range is validated with waste wood of varying qualities.

Unexpectedly, waste paper residues ("reject") give very poor yields (8 mol. %). In fact, a prior washing with acetic acid increased the yield to 65 mol. %. Olive residues and rayon residues show yields of 39–45 mol. %, respectively, but beet root pellets and moringa exhibit inferior yields, which is possibly due to relatively high ash and low cellulose content in the case of moringa. With straw, yields of 55–75 mol. % have been obtained but difficulties arise from the low density of the material. Only a fourth of the solid loading compared to beech and softwood could be achieved at technical scale with straw. This low solid loading is likely the

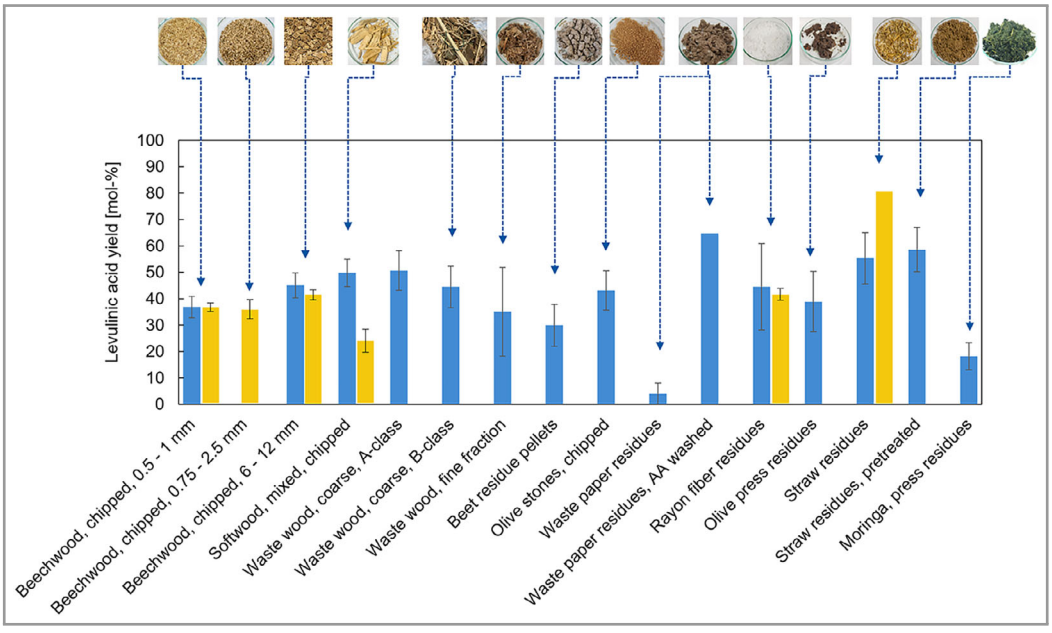

Figure 2. Molar yields of levulinic acid for tested biomass (blue bars = lab-scale; yellow bars = 50-L scale in NGP[2] Biorefinery). Error bars (grey lines) are supplied if replicate experiments are available.

Table 1. Particulate properties of different biomass types/feedstocks (raw data in SI, Tab. S1).

	Wood	Dry residues	Wet residues	Herbaceous residues
	Spruce, beech, waste wood (quality A & B)	Beet pellets, olive stones	Olive pulp, rayon, paper rejects	Moringa, straw
Bulk density [kg m^{-3}]	150–320	440–850	340–1135	44–200
Water content [wt %]	6–18	9–10	46–79	10–71

reason for the high yield. However, the obtained levulinic acid concentration is inferior, which indicates a trade-off between loading and purification effort.

The presented results demonstrate the variation spanned by different feedstocks. The experimental data with various wood types indicate a considerable effect of size selection and wood species. Also, some materials, e.g., paper rejects, require individual treatment to avoid neutralization of the acid catalyst by inorganic ions. This way, yields > 60 mol. % can be achieved, while an average yield of 44 ± 15.5 mol. % is obtained. Individual process parameters (e.g., residence time, acid concentration, etc.) might enhance the yield which has to be tested.

Regarding processing, the materials differed a lot regarding water content and bulk density (cf. Tab. 1 for own measurements, further data on density of different types of biomass can be found in [20]). The feedstock basically spans four categories: biomass residues from wood and herbaceous plants are characterized by rather high density and low water content or vice versa. Industrial residues (olive pulp, rayon, paper rejects) show high bulk densities which is due to high water content in water-retaining fibers. Non-fibrous or preprocessed residues (olive stones, beet pellets) even exceed the density of wood and usually show much smaller variations in water content (cf. Tab. S1 in SI). These individual properties determine flowability and compressibility [21] influencing the choice of equipment for solids processing.

3.2 Technology Assessment for Solids Handling

3.2.1 Solids Feeding into Reactor

The task in the designed process (Fig. 1) is to enable robust continuous feeding of solids (0.5–30 mm) against a pressure of 14 bar(g) into a corrosive atmosphere. The solids loading is key as it directly impacts the output of the reactor volume. The pumpability of biomass feedstock is seldomly addressed in literature but feeding options for hydrothermal liquefaction have been reported [21]. High solid concentrations (>15 wt. % dry solids) and larger particle sizes (2–5 mm) limit pumpability. Inversely, pumpability increases with finely ground wood (30 µm) but costs likewise increase considerably for a particle size below 2 mm. Extensive fibrous morphology (e.g., straw) generally complicates transport and pumpability.

In this work, the process parameters constrained the selection of feasible technologies. Lobe pump manufacturers could only offer pumps with insufficient pressure difference (≤3 bar), although some reports claim much higher pressures [21]. Similarly, rotary feeder valves lack the necessary pressure difference in standard designs; although special designs are reported (e.g., 40 t h^{-1} and 14 bar, [22]). The reported plug-forming and non-plug-forming piston feeder (cf. [23] for the engineering of such equipment) could not be obtained on the German/European market.

This leaves four types of feeders (Tab. 2 cf. [24] for further review). The first technology is progressing cavity pumps. It feeds a slurry mixture by positive displacement using a steel rotor in an elastomer-based stator. This type of pump is ubiquitously employed in industry and provides continuous flows with low pulsation. In contrast, a piston slurry pump works semi-continuously achieving a high-pressure difference by reciprocating piston action, creating suction and discharge phases.

Lock hopper systems feed solid material across a pressure difference by staged opening and closing of valves on the top and bottom of an intermediate pressure vessel (the so-called "lock hopper"). A prerequisite for a simple design is free-flowing, non-clogging material which can be charged and discharged into the pressure vessel by gravity. Before discharge of the material into the pressure vessel the lock hopper is pressurized, typically using inert gases [22]. The energy demand rises with pressure difference because the gas volume has to be compressed every cycle and bleed gas has to be considered [23, 25]. The use of water as incompressible fluid [26] would be favorable but seems not available commercially.

The fourth technology for feeding solid material against pressure is plug screw feeders. This technology is applied in the pulp and paper industry [22, 25]. The raw material is densified in a conical screw to form a pressure-sealing plug, which breaks up at the outlet and falls into the reactor. The plug formation is critical as it seals the reaction pressure and depends on the design of the screw and the biomass [27]. Compressibility is important but can lead to decreasing mass flow [28].

The comparison of the different technologies for solid feeding shows drawbacks of each technology for the application in the case study (cf. Tab. 2. The main disadvantage of progressing cavity pumps for slurry feeding is the required pumpable suspension. Conducted experiments

Table 2. Comparison of different biomass feeding technologies against pressure levels of $p >= 14$ bar(g).

	Slurry feeder pump Progressing cavity pump	Slurry feeder Piston slurry pump	Lock hopper	Plug screw feeder
Capacity*	1–200 m^3h^{-1} slurry = approx. 0.1–20 t h^{-1}	1–200 m^3h^{-1} slurry = approx. 0.1–20 t h^{-1}	0.01–100 t h^{-1}	10–100 t h^{-1}
Max pressure difference[a)]	<20 bar	>100 bar	≤40 bar (≤10 bar at 180 °C)	15 bar [24]
Input	Slurry	Slurry	Solids	Solids (compressible)
Energy demand[b)]	Low	Medium	High	Medium to high
Investment cost[c)]	26 000 € · $c^{0.56}$	100 000 € · $c^{0.96}$	n.a.	n.a.

a) Vendor specification; b) Classification into "high" and "low" represents a difference of two orders of magnitude; c) Capacity c in m^3h^{-1}, reference year 01/2025.

showed pumpability with cellulose up to 20 wt % solids of pure cellulose powder in water (ca. 250 µm), which decreases with impurities. Pumpability of wood chips (0.5–2.5 mm) up to 18 wt % in water could be validated at a vendor's test facility. Larger chips (<40 mm) were only pumpable up to 7 wt % dry solids. Furthermore, any constriction in piping and the particle speed are crucial factors in preventing separation and plugging. Therefore, additional water is required for robust operation, and the necessary comminution of particles imposes a constraint on the flexibility of processing different raw materials. Further, the longevity of stator and rotor material against wear determines functionality. The required chemically inert material likely requires multistage pumping systems for the given pressure difference. Piston pumps in contrast are powered by hydraulics and can handle pressures > 100 bar. However, the material requires particles to be embedded in a viscous, compressible matrix to be effectively sucked into the piston. In addition, it is four times more expensive than the eccentric screw design (cf. Tab. 1 and Fig. S1).

The lock hopper and the plug screw feeder are capable to feed dry material against pressure. The lock hopper requires compressed gas or steam from the reactor, which is a significant energy loss and can cause clogging due to condensation. A prerequisite is good flowability of the material. The selection of valves is crucial, as resistance to wear, low cost, and resistance to pressure vs. temperature is mutually exclusive. In fact, the authors did not find polymer-sealed valves to withstand the combination of 180 °C and pressures differences > 10 bar. The plug-forming screw feeder could not be tested and was not economically feasible at smaller scale.

The comparison shows that each raw material requires a tailored design for the feeding equipment. Slurry feeding is limited at 7–20 wt % of solids depending on material properties. Clearly, the smaller the particle size and the larger the capacity-to-particle size ratio, the easier the pumpability but limited also by long, fibrous morphology. Feeding of solids only can be established with high efforts in energy and costs and they resemble more an additional package unit than a standard design.

3.2.2 Solid-Liquid Separation

The task of solid-liquid separation is to separate residual non-cellulosic solids after conversion. Since the reaction medium still retains a temperature of up to 100–120 °C after flashing, the equipment must withstand the harsh reaction conditions while also accommodating particle sizes comparable to the feedstock along with fines formed during conversion. As the separation technology handles hot and volatile components, potentially under pressure, it must be technically tight to ensure safe operation and working conditions.

Eligible mechanisms of particle separation are either based on size or gravity. Separation by gravity will not be in the focus of this work, as centrifuges, hydrocyclones, or decanters cause high investment costs, and vendors have raised concerns regarding the stability of operation (e.g., for batch processing only, corrosion issues, low solids contents). Similarly, settling tanks are appropriate for wastewater clarification but are not designed for tight operation. The industrially proven filter press suffers from the same issue and is rather difficult to operate continuously without manual supervision. Rotary pressure filters were not considered due to issues with abrasion that would damage the sealings.

Technologies considered in this work are listed in Tab. 3 Simple screens operate based on gravity-driven flow and surface filtration, using a curved, slotted screen to separate solids (>250 µm) at the bottom without the need of external energy [29]. Similar principles are applied in spiral sieve, which transports solids from the (unpressurized) liquid by a screw, or in an inclined belt filter, which transports a filter cake on endless metal belts or fleece. All these technologies are favorably simple in design but the modification for pressurized or vapor-tight operation is difficult. In addition, they fail at high solid loadings or operating with low-density material.

While vacuum belt filters use pressure difference to improve filtration, they can hardly be operated vapor-tight and under elevated system pressure. The maximum solid loading at the inlet of each of these technologies is determined by the flowability of the slurry, as the particles

Table 3. Comparison of different technologies for solid-liquid separation.

	Slurry feeder pump Progressing cavity pump	Slurry feeder Piston slurry pump	Lock hopper	Plug screw feeder
Capacity[a)]	1–200 m^3h^{-1} slurry = approx. 0.1–20 t h^{-1}	1–200 m^3h^{-1} slurry = approx. 0.1–20 t h^{-1}	0.01–100 t h^{-1}	10–100 t h^{-1}
Max pressure difference[a)]	<20 bar	>100 bar	≤40 bar (≤10 bar at 180 °C)	15 bar [24]
Input	Slurry	Slurry	Solids	Solids (compressible)
Energy demand[b)]	Low	Medium	High	Medium to high
Investment cost[c)]	26 000 € · $c^{0.56}$	100 000 € · $c^{0.96}$	n.a.	n.a.

a) Vendor specification.

must distribute evenly over the given area. Additionally, the slurry has to be pumpable, which limits solid loading below 10 wt % in this case (see above). The screw filter press transports the medium from the inlet to the press chamber using a screw while simultaneously pressing the liquid through a screen. Depending on the design, a screw filter press can either process slurries using a back pressure regulator at the end or by having the flights of the screw itself to increase the pressure to dewater solids.

In this study, technical-scale experiments demonstrate the feasibility of filtration using a Nutsche filter (Seitz Enzinger Noll EF-45-65CWF, 65 L) with a standard filter cloth (MN 1672, Machery-Nagel) resulting in a reliable dry matter content of approx. 30 wt %. Similar results are obtained in experiments using a vacuum belt filter (BHS BF 010-010). A screw filter press shows similar results (25–35 wt %) but in continuous operation combined with the handling of large volume streams of liquid. In contrast, a screw press reaches dry solids content of 65 wt % but requires solids inlet at rather low capacity. Hence, a screw filter press for slurries is the best compromise between capacity, dry solid output, and particle separation efficiency for solids separation.

3.3 Legal Assessment

This section addresses the approval processes in view of the timelines and requirements. It is essential to differentiate between the stage of plant engineering and the stage of operation and sales. The latter requires the following of standards and regulations regarding product safety, greenhouse gas emissions, etc., which have to be considered as the producer. However, the initial step in the transition of fossil-based industry to bioeconomy is a successful plant engineering to realize a feasible process. Besides the well-known engineering stages of process design, eligibility for approval becomes key [30]. The erection of such a processing plant requires approval according to the Federal Immission Control Act including building permission and environmental impact analysis. The latter can involve GHG analysis and REACH certification (which is the case for levulinic from 100 to 1000 t/a; cf. [31, 32]), but which depends on capacity and the business model. Hence, we focus on the legal aspects involved in plant engineering in this work.

The comparison covers a decentralized and central production; the latter is realized as a "greenfield" project. The decentralized scenario employs a decentral preconversion step of 1000 t/yr input capacity. The main areas of approval in Germany are land-use planning, Federal Immission Control Act, building permission, and environmental impact analysis. They apply to both scales but differ in complexity. While the Immission Control Act leads the permission process, a location at an already registered site can facilitate the approval considerably, providing that the decentral unit does not emit pollutants that are not covered by the main site. Similarly, established sites benefit from existing land-use plans facilitating building permits. The environmental impact analysis and the approval procedure according to the Immission Control Act can be simplified due to the smaller size of the unit.

To quantify the benefit, the authors conducted interviews with operators and authorities in Germany for that purpose [33]. The development of a binding land-use plan for a greenfield project takes several years at a very early stage in planning. Together with a full approval process for emissions, building permit and environmental impact, it can easily take four years before the start of construction. In contrast, a decentral concept can be approved in half to one year. Decentralized production thus has to follow the same regulations but benefits from simplified approval processes when located next to existing facilities. This can accelerate roll-out once one hub-and-spoke has been established.

3.4 Economic Assessment

Two scenarios of decentral and central preconversion of 200 000 t/yr of raw material to levulinic acid are compared for economic prospect (Tab. 4. The design of a decentral preconversion plant has a modest input capacity of 1000 t/yr and direct equipment cost of 1.5 Mio. €. The scenario requires 200 decentral production units integrated into existing industrial infrastructure, hence costs for respective engineering and design do not impact the total capital investment as usual. Direct equipment costs are

Table 4. Economic scenarios of decentral modules vs. central biorefinery conversion of biomass.

	Decentral biorefinery modules	Central biorefinery
No. of units × input capacity	200 × 1000 t/yr	1 × 200 000 t/yr
Direct equipment cost	1.5 Mio. €	45 Mio. €
Total capital investment	300 Mio. €	200 Mio. €
Feedstock cost	20 €/t	130 €/t
Product yield per feedstock	0.2	0.16
Energy cost	0.16 €/kWh	0.08 €/kWh
Further parameters	8000 h/yr, 3 kWh kg^{-1}, 10 yrs depreciation, 10 % interest rate, aux. cost 0.61 €/kg, no waste disposal cost	

assumed equal to total capital investment due to negligible engineering per decentral module. Additional costs for central postprocessing of the material are not in the scope of this work. In contrast, the central biorefinery processing with 45 Mio. € of direct equipment costs translate to 200 Mio. € of total capital investment by a Lang factor of 4–5 [30].

Wood chips as representative biomass are sold in Germany for around 95 €/ton (35 % water content [34]), which equals 130 €/dry ton without tax, marking the established feedstock cost. This includes logistics but also standardization, certification (i.e., recycling management, waste laws or other regulations), and markup. In contrast, residues are not considered as traded products under the Circular Economy Act (Kreislaufwirtschaftsgesetz) and therefore do not have a value but must be disposed of, i.e., paper rejects even cause disposal cost at 40 €/t [35].

In the past, residue prices between 10 and 20 US$/t have been reported at the lower end [36, 37], which is 14–26 €/t in 2025. These figures have not turned out to be realistic for large-scale exploitation but still mark a valid lower bound for a yet undeveloped trade of biomass residues. Hence, 20 €/t is assumed as costs for the feedstock in the decentralized scenario. Following the best-case yield of 70 mol. % in Sect. 3.1, we consider a yield of 0.2 kg kg^{-1} for the decentral scale, while in the central scale, processing of the heterogeneous feedstock is reduced by the standard deviation of 15 mol. %. Decentral energy is more expensive than at a dedicated plant, which is reflected by 0.16 €/kWh vs. 0.08 €/kWh, respectively. This range resembles cheap electricity until 2021 at central sites and the prices in 2024 [38]. To simplify the comparison, energy demand was set to 3 kWh kg^{-1} of product according to own simulations, and in line with the literature (3 kWh kg^{-1} = 2.6 GJ t^{-1} at a yield of 0.24 [39]). Economic parameters of depreciation (10 yrs.), interest rate (10 %), and auxiliary cost (catalyst, liquids, personnel, etc.) are constant in both scenarios.

As the objective was to compare two modes of production, no absolute production cost will be calculated in this work but relative results for central and decentral processing. The analysis of cost distribution in Fig. 3 shows that for the decentral process units the manufacturing costs are dominated by investment, accounting for 41 % of the total production cost. Even in the case of the central biorefinery concept, the investment still represents a significant share of 34 %. Both are much higher compared to the operating expenses of established chemical plants (approx. 10 % of operating expenses, cf. [30]). On the other hand, it can be argued that these processes resemble upstream production of renewable energy where raw materials do not govern the manufacturing cost anymore. In fact, feedstock costs account for only 3 % of the total in the decentralized scenario. Despite the variance in this work given by the cost estimate class 3–4 according to AACE [40], it is clear technology and process intensification become the major leverage in these scenarios. Besides, energy cost could have a major impact in both scenarios (with 8 % or 16 % for central or decentral operation, respectively) but might also offer optimization potential using demand side management.

A sensitivity analysis for the decentral case shows the large influence of product value as it directly impacts margin and profit (cf. Fig. S2). Hence, the case study highlights that product yields have to be very high and/or byproducts have to be valuable to achieve profitability. In fact, the anticipated yield reduction in the large-scale plant by 15 mol. % already results in half the profitability. The second leverage is capacity and operating hours. A reduction by 1000 operating hours per year results in almost half the profitability. This emphasizes the precondition of such plants to run continuously and at both scales. This challenges the feeding section for robustness, redundancy, and maintenance, in particular.

The large impact of investment costs prompts measures to improve the process design in both cases. With set technology for all process steps, the scale can leverage specific capital costs. Clearly, decentral biorefineries could be larger than 1000 t/yr but in accord with decentral feedstock supply. The limitations of large-scale processing become obvious as a standardized supply with beechwood would allow for two locations of a central biorefinery in Germany [41] processing 1 Mio. t/yr. In comparison to the required and available carbon for chemicals, this is a necessary but not sufficient supply of renewable carbon for chemicals.

The alternative is to collect and preprocess a mixture of various residues. At large scale, this would require several processing lines in parallel to deal with different feedstocks. Such a pretreatment section can make up 20 % of the total capital investment [42, 43]. Feeding equipment analyzed in this work reaches this range of direct capital cost (cf. Fig. S1). The central biorefinery would require multiple feeding capacities of 100–180 m^3h^{-1} (dry) or even larger than 200 m^3h^{-1} with slurries at 15 wt % solids. We calculated that if such additional equipment exceeds 23 Mio. €,

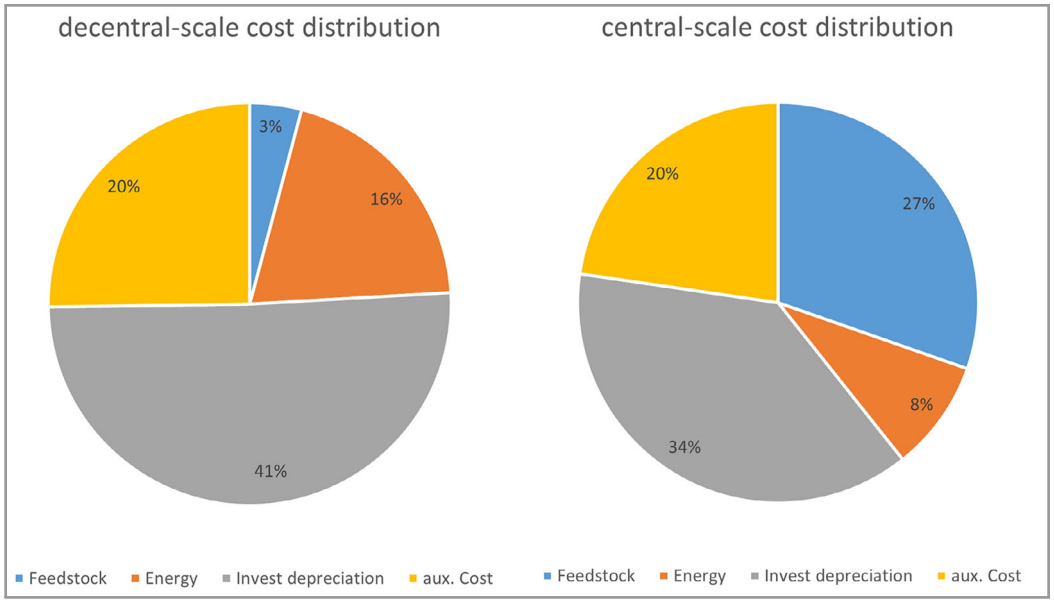

Figure 3. Distribution of manufacturing cost for the decentral preconversion step (left) vs. the central preconversion (right).

the investment becomes more expensive than the decentral biorefinery modules. This indicates that the more diverse the feedstock, the less advantage for central processing. Feedstock heterogeneity and distribution thus pose opportunities for sustainable and robust chemical value chains, but processes need to be optimized for high yield and low investment. A modular design to exchange technology without (re-)engineering the whole process is key and could be realized by applying principles of modular type package automation [44].

4 Conclusion

The transition from central processing of (imported) raw materials to a decentralized exploitation of domestic renewable carbon sources is addressed. The heterogeneity of biomass and lignocellulosic residues results in a variability in process yield which is demonstrated in a case study of levulinic acid production from lignocellulosic biomass. The observed variance emphasizes that the variety of raw materials requires tailored preprocessing strategies. However, scalable technology is scarce for feeding of heterogeneous residues.

Economic analysis indicates that a multitude of decentral production units can compete with central processing units when tailored to the feedstock to achieve almost optimal yields. However, their process and equipment design must be optimized for robust and autonomous 24/7 operation. Combined with modular engineering, this could pave the way for both viable and sustainable carbon value chains in chemical supply. If established at existing sites, realization may also benefit from facilitated permission for decentralized processing.

Supporting Information

Supporting information for this article can be found under DOI: https://doi.org/10.1002/cite.202500043.

Acknowledgment

The authors thank Thu Tram Julia Pham, Roberto Martínez Brizuela, Verena Hunstig, Michelle Freyer, Lena Müller, and Umar Wahabzada for their valuable support. This work was financially supported by the Bundesministerium für Bildung und Forschung (BMBF) by grants within the Modellregion, BioRevierPLUS: InBio, Innovationscluster Integrierte Bioraffinerie, Teilprojekt DeMoBio) project, with project no. 031B1135B, 031B0918E and 031B1135C.

Open access funding enabled and organized by Projekt DEAL.

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