Annex 10

to Contract No. 6-1/42 of 30.09.2024. On the implementation of the project within the scope of the State Programme ""Research and Sustainable Use of Local Resources for the Development of Latvia" 2023-2025"

Form for the Final Scientific Report of the Project

Project title: **Innovation in Forest Management and Value Chain for Latvia's Growth: New Forest Services, Products and Technologies (Forest4LV)**, No. VPP-ZM-VRIIILA-2024/2-0002

Summary

The State Research Program **Forest4LV** significantly advanced sustainable forest management, forest-based bioeconomy, and wood-based product innovation in Latvia. Forest studies enhanced understanding of genetic adaptation, growth responses, and biodiversity, demonstrating the benefits of assisted gene transfer and the sustainability of intensive forest management while maintaining genetic diversity. Automated regeneration systems, soil amelioration, and advanced FTIR-based diagnostics were developed, supporting evidence-based management, circular economy fertilization practices, and climate resilience. The research strengthened international recognition, collaboration, and competitiveness, informing policy by guiding seed source adjustments, salvage logging regulations, and soil and forest health monitoring. Extensive field experiments and remote sensing analyses improved understanding of pest outbreaks, non-lethal disturbances, and tree-related microhabitats, contributing to resilient forest landscapes. Educational outcomes included integration of results into doctoral, master and bachelor programs, internships, and training courses, fostering skills development and professional visibility. The **Forest4LV** also developed high-value wood and bio-based products and technologies, including thermally modified veneers, polymer composites, extractives, platform chemicals and ecological binders, creating industrial applications and supporting circular economy goals. Knowledge transfer to policymakers, industry, and the public ensured societal impact, enhancing forest sustainability, resource efficiency, and awareness of environmentally friendly practices, while positioning Latvia as a competitive hub for forestry research and bio-based innovation.

Partners

- Latvian State Institute of Wood Chemistry (**LSIWC**)
- Latvian State Forest Research Institute "Silava" (**Silava**)
- Latvia University of Life Sciences and Technologies (**LBTU**)

1. Scientific excellence

WP1 conducted a comprehensive and multidimensional set of studies to enhance the understanding of the resilience, productivity, and biodiversity of forest ecosystems under changing climatic and management conditions. The analyses focused on tree growth and adaptive responses along genetic, climatic, and edaphic gradients, with particular attention to Scots pine populations in the Baltic region. The work assessed the impact of improved breeding stock on genetic diversity at the landscape scale, the interaction of restoration methods, soil preparation, and thinning practices, and the role of abandoned trees and tree-associated microhabitats in biodiversity conservation. The impact of natural disturbances such as wind, fire, and pest outbreaks on tree survival, growth, and forest resilience was also evaluated. Furthermore, WP1 improved precision forestry tools, including innovative methodologies for assessing nutrient requirements and predicting forest stand responses. Overall, the results provide a solid scientific basis for adaptive, sustainable, and multifunctional forest management in the Baltic region.

T.1.1. Improved adaptation - ***A.1.1.1 Genetically determined differences in reaction to weather extremes as modified by environment (forest type):*** Analysis of radial increment across climatic and edaphic gradients characteristic for the Baltics was accomplished providing comprehensive estimates on genetic differences in growth responses among European populations, as well as on the adaptive potential of local Baltic population of Scots pine in terms of

environmental plasticity of radial increment. A synergy of time series analysis and quantitative genetics was used for the analysis of data. Additionally, aspects of the molecular genetics of responses to environmental extremes were assessed. The Northern/Eastern European conifer populations showed presence of local genetic adaptation to whether fluctuations across regional climatic gradient. The genetic control over increment were modulated by edaphic conditions, however for local population, these effects were rather weak. The genetic effects manifested during the recovery following weather anomalies. ***A.1.1.2 Effect of reduced number of genotypes in propagation population on genetic diversity at the forest landscape scale:*** Under the intensifying forest management in Northern Europe and the Baltics, which implies wide application of improved forests regenerative material, which originates from nurseries, concerns about the depletion of genetic diversity of forest stands arise. To clarify such doubts and develop a roadmap allowing to avoid such a problem, simulation analysis for Scots pine based on genotyping of nurseries and wild native populations was conducted testing scenarios, where various set of nurseries were used as the seed sources. Sparing application (up to 40% of landscape) of improved material increased the genetic diversity, while for wider usage, the clonal diversity became at play. Furthermore, application of a mixture of seeds originating form nurseries representing > 20 different clones each, had explicit positive effects on genetic diversity of the forested landscape. Still, rare alleles might be depreciated. Nevertheless, the current findings support the efficiency of adaptive forest management also in terms of maintaining genetic diversity of forests. ***A.1.1.3. Interaction effect of plant material × soil scarification × regeneration method and thinning. Effect of initial application of green energy production by-products***: The activity had two subordinate objectives, one of which was agilely altered according to the current needs from the industry. To disentangle the complex management interactions under contemporary adaptive management practices, a set of parallel experiments testing origin of seed material, soil preparation, and regeneration type were resampled, based on which mid-term effects were estimated. According to the estimates, seed origin and retention type had significant effect on tree dimensions and growth under harsher conditions in nutrient poor sites. Demonstration objects for CSF and RFFL were established within the experiments and included in respective international networks. The second objective was altered to complement the first objective, hence the distribution of sampling roots according to soil preparation. Considerable differences were estimated between disc trenching and mounding, the later showing much more desirable distribution of seedling roots in terms of mechanical stability and resource acquisition. The initial goal of the second objective was met by the assessment of mid-term assessment of reclamation of gravel extraction sites. The evaluation of tree regrowth and ground cover vegetation highlighted explicit positive effects of introduction of fertilizers (green energy by-products) and the surrounding stands, highlighting the potential of intensive forest management to expeditiously regenerate general ground cover and epiphyte communities promoting biodiversity.

T.1.2. Advanced forestry - ***A.1.2.1. Success of natural regeneration in challenging sites (peat soil) in comparison to sowing, and effect of sowing on genetic composition of stands.*** Containerised seedlings have been considered as a standard for regeneration of stands with improved reproductive material, however considering increasing labour costs, automated sowing is being revisited as. In contrast to planting of containerized seedlings, sowing rise doubts about the efficiency of introduction of improved material due to mortality and seed predation. High efficiency of sowing in terms of introduction on improved regenerative material was verified busing molecular genetic methods, which reliably linked >85% of Scots pine saplings in sown plantation as progenies of nursery mother trees. As the establishment of Scots pine requires disturbed soil, the effects of supplementation of seed lot with a small quantity of mineral soil was subsequently evaluated in terms of survival and growth. The improvement of seed lots before sowing with a small amount (50–100g) of sand on organic soils improved establishment and survival of seedlings, which showed positive effects on growth and competitiveness in a short term. Hence, the observed effects provide solid basis for development of forest regeneration using automated systems/drones. To increase the biological diversity in hemiboreal coniferous forest, pedunculate oak is one of the key tree species. Hence automated sowing of oaks can be implemented. However, due to size of acorns, multiple seeds per lot are difficult to sow, hence the germination ability of individual seed is paramount. To clear these issues oak seedling emergence was assessed in an international collaboration to evaluate the potential of sowing across Europe to meet the set climatic and restoration goals. The explicit primary effect of seed quality was determined, highlighting the relevance of seed orchards and seed delivery systems. ***A1.2.2. Probability of regeneration success as influenced by shelter treatment.*** Continuous cover forestry is recently becoming increasingly topical often considered as a panacea for naturalness and eco-friendly forestry. However, the shelterwood remaining after harvesting is obscuring

light conditions, which often prevents regeneration of light demanding species, such as Scots pine, although the effects are regional. To clarify these issues for Scots pine in hemiboreal forests, a considerable (150 stands) sampling was done evaluating properties of both shelterwood and regenerating (advance regeneration) properties. Regeneration density of scots pine showed a hyperbolic negative relationship with shelterwood density with rapid decrease in the range when density of shelterwood was 0-300 trees per ha. This decisively highlighted the unsuitability of Scots pine to continuous cover forestry, when harvesting is homogenous and no wider openings are not created. Thence continuous cover forestry would inevitably reduce the abundance of scots pine gradually replacing it with shade tolerant species, thus altering forest landscapes. ***A1.2.3. Tree related microhabitats on veteran trees.*** Under intensifying management, conservation efforts also need to intensify, particularly in managed stands. For this purpose, while avoiding the infringement of timber production and C sequestration functions of forests, alternative methods are under scrutiny. In this regard, tree related microhabitats, which are important for a spectrum of organisms have appeared as a promising tool for providing additional habitats in commercial stands/plantations, which otherwise would be homogeneous. For this purpose, the overall occurrence of microhabitats (TREMs) was assessed based on special part of NFI, and the relationships with tree and site properties estimate. The occurrence of TREMs showed species specific relationships with tree size (DBH), while the abundance increased as the trees died, highlighting the advantages of deadwood. As the retention forestry is the main model in the Baltics, the occurrence of TREMs on retention trees was compared to veteran tree, thus assessing the potential richness of TRMS trees in managed forest landscapes could realistically reach. The estimates for retention and veteran trees were comparable and exceeded those for general stands. ***A1.2.4., A1.4.2. Survival of retained trees after shelterwood harvest and retention trees in clear-cuts***. Storms are the main, yet still intensifying natural disturbance in the Baltics, which are causing severe damage to standing stock, particularly in recently harvested stands. Retention trees are particularly vulnerable in this sense, yet management and site conditions can affect their susceptibility to wind damage, as well as their survival and ecological functions provided. Hence there is an necessity to evaluate survival of retention tree, particularly based on remote sensing. Accordingly, a model for detection of retention trees in stands of different density was calibrated based on aerial imaging, and verified on site. Employing the calibrated model, retention trees were identified in harvested stands based on available reconnaissance cycles, thus forming survival time series. The estimates suggested that retention trees can survive more than 30 years affectively becoming veteran trees; while their mortality is somewhat higher during the first 10 years after harvesting. Nevertheless, also dead retention trees provide functions desirable for conservational purposes. ***A.1.2.5. Species diversity, growth in different soil and hydrological conditions***. For the first time, data were compiled and published on the role of vegetation in biomass formation and carbon (C) sequestration in worked-out peat extraction areas amended with wood ash. It was concluded that the initial increase in biomass was ten times higher than the contribution of planted trees (A.1.2.5.). A manuscript was prepared on the results of the gradual reclamation process of sand and gravel quarries over a period of 9–32 years. The study concluded that biologically valuable lichens are already present on tree stems in these stands (A.1.2.5.). A conference presentation and a scientific paper were submitted on the effectiveness of organic soil amendments (pig, cattle, poultry manure, sheep wool) when establishing plantations in sand and gravel quarries (A.1.2.1.). Previously collected information was compiled on the affiliation of genetically surviving Scots pine material in sown areas after tending to the seed orchard from which the seeds used for sowing were obtained. It was concluded that at least 75% of the trees belong to this seed orchard (A.1.2.1.). Information was compiled and analysed on the relationship between root system architecture formation of planted Scots pine, Norway spruce, birch and black alder in young stands and the method of soil and planting site preparation – mound or furrow (A.1.1.3.). At conferences, the Latvian forest management related long life education system was presented and described (D2.2.). A conference presentation was delivered and a manuscript submitted for publication on alternative forest management scenarios, focusing on increasing the proportion of protected forest areas and analysing the associated socio-economic impacts (D2.2.) Together with **LSIWC** and international partners a programme was prepared for Baltic and Nordic doctoral courses scheduled for 14 September 2026 (A.1.1.3. & D2.2.). Teaching materials were prepared and supplemented for a already ongoing lifelong learning course “International Sustainable Small-scale Forestry I” for forest owners in cooperation with Linnaeus University and the Latvia University of Life Sciences and Technologies (D.2.2.) A successful proposal was prepared and submitted to the European Union Horizon Europe programme call HORIZON-CL6-2025-03 – BloomEra (A thematic network to bloom the farmers’ income by innovative agricultural systems for arable crops and by the circular use of their agricultural residues; Project No. 101295871), as well as to the Fundamental and Applied Research Programme project “Potential of

Non-Wood Forest Products: Linking Forest Bioeconomy with Social and Cultural Aspects" (LZP-2025/1-0478). Both projects ensure the transfer of knowledge generated in the studies, data analysis, and the publication of results in both popular science and scientific periodicals. ***A.1.2.6. Persistence of genetic gain after thinning with various intensity and site amelioration***. The persistence of breeding effects following thinning, which is amelioration of growing conditions, have been debated. It has been suggested that thinning reduces breeding effects, thus rendering tree breeding programmes economically questionable. To contribute to clearing this issue, long term progeny trials with complete information on its structure and history, following thinning were sampled. The pre-and -post thinning breeding effect and heritability of productivity traits were estimated and compared, which indicated persistence of the breeding effect also under ameliorated conditions after thinning, thus providing additional arguments for implication of breeding programmes. ***A.1.2.7. Assessment of interaction affect in the conditions of Baltic artesian basin***. In the Baltics, precipitation exceeds evapotranspiration, resulting in overmoist conditions, hence waterlogged sites are common. Furthermore, the overmoist stands occur in sites with ground water discharge. To increase their productivity, in the 1960s vast drainage systems were constructed, which have reached the age, when renovation is needed. Though due to climatic changes, forests within the region are increasingly subjected to water shortages, hence restoration of efficiency of drainage can be ambiguous. To clear these issues, the relationships between sit index and ground water discharge was evaluated, indicating that water excess in discharge areas ahs still been limiting productivity, necessitating drainage. The direct effects of drainage renovation of changes in increment were evaluated based on changes in radial increment, and the analysis showed that in most cases, the drainage maintenance/renovation showed no significant effect. However, for Norway spruce drained mineral soils likely without ground water discharge, over-drainage might occur, as indicated by systematic decrease of increment in response to water shortage. ***A.1.2.8. Development of technology for assessment of requirements of nutrients and prediction of stand response***. The project developed an innovative accredited FTIR spectroscopy methodology for characterising foliage nutrient status, validated on 1697 samples. By capturing complex interactions like biomass dilution and ion competition, this technology outperforms direct measurements. It establishes a robust, integrated approach for predicting forest stand responses to soil amendments, significantly advancing precision forestry diagnostics.

T.1.3. Increased vitality: ***A.1.3.1. Effect of non-lethal wind and fire on growth***. The intensifying effects of natural disturbance is causing additional stress to surviving trees, which can facilitate legacy effects, such as outbreak of pests and diseases. Hence assessment of recovery and responses to non-lethal disturbances for surviving tress is advantageous for proactive and agile management aiming at sustainability of forests. The effects of non-lethal natural disturbances on surviving trees were assessed based on analysis of increment. The responsiveness of increment of scots pine to a severe yet non-lethal fire was expressed as decreased growth, which was followed by ameliorated growth allowing trees to stabilize under altered site conditions. Though the sensitivity and hence growth patterns altered towards higher drought sensitivity, likely as increment became higher and more plastic. Non-lethal wind disturbances can cause intrinsic wood damage that can facilitate occurrence of physiological drought which can reduce growth or increase sensitivity of increment. the evaluate the strength of such effects on pine growth, stands surviving various wind events during a summer storms were sampled in landscape that was severely damaged, and from which the maximal wind speeds were known. In 15 stands increment cores were collected and tree-ring widths were measured. Although no direct relation in post disturbance growth was not apparent, the post disturbance additional increment varied greatly among stands. The current result of this is dataset and initial analysis. Additionally, large scale analysis of disturbances across landscape revealed the relevance of surrounding undisturbed forests for facilitation of natural recovery of the severely disturbed patches. This highlight the paramount role of trees surviving non-lethal disturbances on resilience of the forest landscapes that are facing intensifying natural disturbances. **A.1.3.2. Effect of *Ips acuminatus* in combination with wood inhibiting fungi on survival and increment**. The projected climatic changes in combination with intensifying effects of natural disturbances are anticipated to increase the possibilities and magnitude of pest outbreaks. Early warning through can help to mitigate the effects of advancing outbreaks by timely proactive management, particularly by eliminating the sources of outbreaks. For this remote sensing based on satellite images is among the most effective means. However, the identification of damage patches (potential sources of outbreaks) inn managed highly heterogeneous forested landscapes can be challenging, hence the effectiveness can be decreased. To evaluate the accuracy of detection of damages by Ips typographus, random spruce stands in three locations in Latvia, that were classified based on multispectral satellite

images were checked by high-resolution UAV imaging, paying attention to false positives and false negatives. The UAV image analysis revealed that satellite images were unreliable for identification of potential outbreak sources, yet the errors were related to stand and patch properties, inclusion of which in detection systems can improve accuracy and identification or regions, where costlier UAV reconnaissance is advantageous. Besides Ips typographus, Ips acuminatus is emerging as a threat for Scots pine in Europe. The pest is not as aggressive, allowing for early detection and proactive management, yet it is also known to for the ability to spread wood decaying and bluing fungus, which reduce the economic returns from salvage logging. Hence, the fungal communities on Ips acuminatus were identified by molecular genetic methods for material sampled in commercial stands across Latvia. Involvement of Ips acuminatus in spread of bluing and wood decay fungus was confirmed indicating the economic effects of the spread of the pest. The populations of pests are controlled by natural enemies, yet the equilibrium between the predators and prey might be distorted by natural disturbances facilitating outbreaks of the prey(pests). To evaluate this hypothesis, two populations one endemic and one epidemic (post disturbance) were sampled for natural enemies od Ips acuminatus. The estimated differences in communities of natural enemies supported the loss of equilibrium between predators and prey following natural disturbances highlighting the relevance of disturbance legacy effects under intensifying climatic changes. ***A.1.3.3. Effect of admixture and regeneration method on winter and summer browsing damages***. Scots pine (Pinus sylvestris) is one of the most suitable and economically valuable tree species in Latvia's forest sector. By understanding how different silvicultural practices can be used to minimize potential damage to young forest stands caused by members of the deer family – moose (Alces alces), red deer (Cervus elaphus), and roe deer (Capreolus capreolus) – it is possible to avoid conflicts with other sectors and to increase the future economic value of forests.

T.1.4. Enhanced biodiversity ***A.1.4.1. Efficiency of groups of retention trees and wet patches to preserve presence of Odontoschisma denudatum***. Nature protections and restorations as well as conservation are increasingly enforced on industries related with biological natural resources. IN the Baltics, nature protection system heavily relies on a network of small protected areas, which are established based on occurrence of indicator species, which are presumed to be rare, threatened/vulnerable specialist, from a predetermined list. The inclusion of species in those lists historically have been subjective, based on abundance presumptions and expert opinion. Given that the species list has considerable economic effects, the bias in underlying causes should be reduced. Such lists often contain a lot of bryophytes. Odontoschisma denudatum, which is among the species which can be used as reason for establishment of a reserve, with the advance of citizen science and inventory of forest, has drastically increased in abundance in Latvia, with > 5000 sites evaluated as habitats. Furthermore, the species, though deemed specialist for old forests, can still be overlooked in commercial forests due to hidden lifestyle and small size, thus adding to bias. The gathered and cleaned data on its distribution suggests that species in nor rare no endangered, whilst preferring mature moist stands, highlighting the need for reviewing indicator list focussing on abundance dynamics rather than expert opinion, i.e. scientific data thus facilitating sustainability and multifunctionality of forests. ***A.1.4.3. Quantitative assessment of changes of forestry effect: on deadwood, admixture and tree related microhabitats during a rotation cycle.*** Dyewood amounts is one of the indicators of naturalness, which has to be nationally reported as obliged by the EU nature restoration law. Furthermore, there are heated debates on the decreasing structural diversity (including age structure) of forests in the Baltics, as well as lack of deadwood. Furthermore, there a uncertainties on the age-related changes in deadwood in managed forest, presuming them inferior to protected forests. To increase the complexity there are forests that are not managed even though management is allowed. To clarify these issues, NFI data was revisited to evaluate the relationships between stand age and deadwood according to management restrictions and dominant tree species. Dominant species had pronounced effects on age effects on deadwood, which were nonlinear. Furthermore, the management restrictions ha lesser effect on age relations than presumed, highlighting sufficiency of current regulation for meeting the requirements of the most recent EU legislations. The mean level of deadwood in Latvia was estimated as the highest among the European countries, where inaccessible (mountainous) areas are not a abundant, suggesting that current levels of deadwood, which, however, bared high spatial variability, as already acceptable in terms of the UE nature restoration Law.

Under **WP2**, for the first time, data were compiled and published on the role of vegetation in biomass formation and carbon (C) sequestration in worked-out peat extraction areas amended with wood ash. It was concluded that the initial increase in biomass was ten times higher than the contribution of planted trees (A.1.2.5.). A manuscript was prepared on the results of the gradual reclamation process of sand and gravel quarries over a period of 9–32 years. The study

concluded that biologically valuable lichens are already present on tree stems in these stands (A.1.2.5.). A conference presentation and a scientific paper were submitted on the effectiveness of organic soil amendments (pig, cattle, poultry manure, sheep wool) when establishing plantations in sand and gravel quarries (A.1.2.4.). Previously collected information was compiled on the affiliation of genetically surviving Scots pine material in sown areas after tending to the seed orchard from which the seeds used for sowing were obtained. It was concluded that at least 75% of the trees belong to this seed orchard (A.1.2.1.). Information was compiled and analysed on the relationship between root system architecture formation of planted Scots pine, Norway spruce, birch and black alder in young stands and the method of soil and planting site preparation – mound or furrow (A.1.1.3.). At conferences, the Latvian forest management related long life education system was presented and described (D2.2.). A conference presentation was delivered and a manuscript submitted for publication on alternative forest management scenarios, focusing on increasing the proportion of protected forest areas and analysing the associated socio-economic impacts (D2.2.)

WP3 advanced the scientific foundations for sustainable, high-value wood products and biorefinery technologies aligned with the European Green Deal. The dominant wood species in Latvia – birch and pine – form the foundation for both traditional wood processing and the emerging bioeconomy. Their full-value utilization enables the creation of high added-value products while simultaneously reducing the use of fossil resources and lowering CO_2 emissions. The circular bioeconomy cycle demonstrates how primary wood and its by-products are transformed into construction materials, furniture, polymers, and medical and chemical products, thereby strengthening Latvia's national economy. Research covered five thematic areas: wood as a material, biorefinery, bio-based polymers and insulation, innovative products from residues, and efficient resource use.

T.3.1. Wood as a material - Research on juvenile wood (JW) of pine and birch (A.3.1.1) provided new insights into anatomical, physical and chemical differences between JW and mature wood (MW). Demarcation ages were established (17 years for birch, 23 for pine), and JW was shown to have lower density, higher anisotropy, and superior capillary penetration. Importantly, JW demonstrated higher resistance to delamination in glued products, confirming its suitability for glued structural elements and enabling higher-value utilization of small-diameter wood from thinning operations. Thermal modification (TM) studies expanded scientific knowledge on aspen, black alder, birch, poplar and pine wood under nitrogen (A.3.1.2) and veneers under vacuum conditions (A.3.1.3). Optimal TM regimes were identified for each species, improving dimensional stability, moisture resistance, and biological durability. The work filled a regional knowledge gap, particularly for nitrogen-based TM of aspen and alder, and demonstrated that TM can transform low-value hardwoods into competitive materials for outdoor applications and plywood production.

T.3.2. Biorefinery - WP3 advanced biorefinery science by developing technologies for producing high-value chemicals from forestry residues. Plywood residues were converted into 5-HMF (A.3.2.1), while bark from pine, birch and alder was processed into catechol-unit-bearing extractives with potential applications in wound-healing materials and bioactive formulations (A.3.2.2). A natural wood composite based on pine sawdust and birch-bark-derived suberinic acids (SA) was developed, demonstrating the feasibility of ecological binders for structural applications (A.3.2.3). The work also showed how forest management practices influence bark chemistry, creating a new link between WP1 forest management trials and WP3 material development.

T.3.3. Bio-based polymers and insulation - Rigid polyurethane foams were synthesized from SA and tall-oil fatty acids (TOFA), representing a major scientific advance in replacing fossil-based polyols (A.3.3.1). The activity established relationships between SA depolymerization conditions, polyol structure, viscosity, and foam performance. Environmentally friendly flame-retardant systems (ammonium polyphosphate, triethyl phosphate, expandable graphite) were evaluated, enabling the development of foams with enhanced thermal stability and reduced flammability. Comprehensive characterization of hydrophilic pine bark extractives and investigation of their condensation with propylene carbonate to obtain bio-polyols provided a foundation for innovative approaches in polymer chemistry, particularly for the development of sustainable polyurethane materials (A.3.3.2). This knowledge highlights pine bark as a highly valuable renewable feedstock for bio-based PU materials, with key properties that may surpass those of materials derived from fossil-based raw materials. Furthermore, the findings represent a contribution to wood and polymeric chemistries, demonstrating the high potential of hydrophilic pine bark extractives for modification and valorisation as macromonomers. Polymer composites with high renewable content were developed using wood-processing residues and

functionalized bark extractives as reactive modifiers (A.3.3.3). These extractives improved interfacial adhesion, reduced viscosity, enhanced filler dispersion and increased mechanical performance, demonstrating that bark-derived chemicals can partially replace petroleum-based compatibilizers. Wood-polymer composites (WPCs) were also formulated using recycled polypropylene and alkaline-treated pine sawdust, with SA acting as an internal lubricant that improved melt flow and reduced energy consumption

T.3.4. Innovative products from residues - Two high-value product lines were developed. Densified, pre-delignified veneer-core materials for osteosynthesis implants (A.3.4.1) - the activity established a scientific foundation for the use of modified and densified wood in implant materials and other high-performance applications, including potential use in electronics and related advanced technologies. While through close collaboration between the two institutes - specifically, the Bioengineering Laboratory of **LSIWC** and the Forest Phytopathology and Mycology Group of **Silava** - a significant step has been taken toward the synergistic integration of two long-standing research directions: the isolation and study of forest-ecosystem-friendly fungi, and the scaling-up of bioprocesses. As a result, a pilot-scale solid-state cultivation process for the Latvian *Phlebiopsis gigantea* isolate PG182, achieving a fivefold increase in spore yield and reaching TRL 6–7 was developed (A.3.4.2).

T.3.5. Efficiency of wood-resource use - Research on cellular wood materials (CWM) and lightweight stabilised blockboards (LSB) improved understanding of structural performance, dimensional stability, and bonding behaviour (A.3.5.1 and A.3.5.2). TM veneers bonded with SA-based adhesives were evaluated, and LCA methodology was integrated into plywood development through specialised training (A.3.1.3).

Overall, **WP3** delivered interdisciplinary, experimentally validated, and internationally competitive research results that significantly expand Latvia's scientific capacity in wood chemistry, materials science, biorefining and sustainable product development.

2. Impact

2.1. Impact of the project and its outcomes on the development of the relevant fields and the research community in Latvia and its international competitiveness

WP1: The results have a significant impact on forest breeding and management by strengthening the theoretical foundation for breeding programmes and demonstrating the clear advantages of assisted gene transfer, given the limited adaptive potential of local genotypes for climate-related traits. The outcomes substantially enhance international scientific recognition and collaboration, improving the competitiveness of the research team. Importantly, the findings strongly support the sustainability of intensive adaptive forest management, providing robust evidence that genetic diversity in Scots pine stands can be maintained while enabling rapid, science-based adjustments of seed source use in accordance with recent EU legislation. Furthermore, the results deliver high-impact guidance for resilient forest recovery, circular economy–based fertilization practices, and achieving climate and emission reduction goals.

The results provide a strong foundation for advancing automated forest regeneration systems, demonstrating that successful sowing combined with seed lot amelioration is effective even under challenging site conditions and promotes collaboration with forest machinery developers. Genetic diversity assessments of seedlings from improved reproductive material contribute critically to long-term genetic monitoring and sustainable stand renewal across generations. The study offers valuable evidence for policymakers by showing limited sustainability of continuous cover forestry in Scots pine stands, while enhancing international visibility of the research team. Advances in the understanding of tree-related microhabitats (TREMs) and the integration of remote sensing, machine learning, and calibrated models strengthen forest health and damage monitoring under increasing automation. The project also enabled successful Horizon Europe and national research proposals, ensuring knowledge transfer and dissemination. Additional outcomes include improved insights into genetic effects of thinning, water regime management under moist lowland conditions, and the development of an accredited FTIR spectroscopy method, significantly enhancing Latvia's forest diagnostics capacity and international competitiveness.

The research delivered high impact by strengthening international and national collaboration, enabling the upscaling of disturbance analyses and improving preparedness for forest management under increasing risks. Close cooperation between scientists and industry directly identified critical knowledge gaps and significantly enhanced the effectiveness of early warning systems, into which the results are already being implemented, demonstrating clear knowledge transfer and innovation. Extensive field experiments across multiple districts, supported by collaboration with research institutions and forest management companies, generated robust, spatially representative data on the effects of salvage logging on forest pest propagation. The use of permanent sample plots and pheromone-based monitoring substantially improved understanding of pest dynamics. Importantly, the study complements existing knowledge while clearly demonstrating the need for longer-term datasets to better capture forest responses to environmental variability, thereby strengthening the scientific basis for adaptive and risk-resilient forest management.

The results highlighted the need for scientifically grounded evaluation of species lists used to restrict forest management, ensuring a balanced and economically viable approach that reconciles timber production with biodiversity conservation. The activity delivered robust estimates of key indicator values, particularly deadwood volumes, required for national reporting under the EU Nature Restoration Law. Its methodological framework provides a foundation for assessing additional legislative criteria, while effective knowledge transfer and engagement with policymakers have increased interest in the research team and stimulated further indicator-based studies.

During of activities performed by **WP2** a successful proposal was prepared and submitted to the European Union Horizon Europe programme call HORIZON-CL6-2025-03 – BloomEra (A thematic network to bloom the farmers' income by innovative agricultural systems for arable crops and by the circular use of their agricultural residues; Project No. 101295871), as well as to the Fundamental and Applied Research Programme project "Potential of Non-Wood Forest Products: Linking Forest Bioeconomy with Social and Cultural Aspects" (LZP-2025/1-0478). Both projects ensure the transfer of knowledge generated in the studies, data analysis, and the publication of results in both popular science and scientific periodicals.

WP3 significantly strengthened Latvia's forest-based industries by developing technologies that valorise local biomass, reduce reliance on fossil-based materials, and support circular-economy principles.

Industrial partners—including Thermory AS, Ošukalns, Niedrāji, Stiga RM, Kronospan Latvia, CROSS TIMBER SYSTEMS, Nordic Plast, ARB POPE, and AmberBirch—provided materials, evaluated prototypes, and expressed interest in TM technologies, SA-based adhesives, particleboards, WPCs, and bio-based foams. The collaboration ensured that research outputs were aligned with real industrial needs.

The P. gigantea production technology has the potential to replace imported stump-treatment products (e.g., Rotstop), strengthening national autonomy in forest-health management. Biorefinery results demonstrated how forestry practices influence bark chemistry, creating a new link between forest management (WP1) and material development (WP3). Functionalized bark extractives developed within WP3 offer a new valorization pathway for bark residues, supporting circular bioeconomy goals and reducing dependence on petroleum-based compatibilizers. Collaboration with the National Research Council of Italy (IBE), **Silava** and **LBTU** strengthened international research links and supported joint publications and prototype development.

Table 1

No.	Cooperation institution / organisation, country	Type of cooperation	Outcome	Time period
1	National Institute for Research and Development in Forestry 'Marin Dracea', Bucharest, Romania	Data sharing, analysis, publishing	Published manuscript	01.01.2025.-11.08.2025
	Lithuanian Research Centre for Agriculture and Forestry	Data sharing, sampling, publishing	Prepared manuscript, conference presentation	01.01.2025-31.12.2025.
2	SIA Rīgas Meži	Sample plot allocation	Field experiment layout	09.2024.-12.2025.

3	Diverse_Gene_Watch (Lithuania, Estonia, Sweden, Denmark, Poland, Germany)	INTERREG Baltic Sea Region projects	Use of genotyping protocols and other methodologies for development of a genetic diversity monitoring system for the Baltic Sea region.	03.2025.-02.2028.
4	Linnaeus University	Education	Materials for Long-life education "International Sustainable Small-scale Forestry I"	09.2024.-12.2025.
5	**LSIWC** and Nordic country scientists (Norwegian Institute of Wood Technology; Norwegian Institute of Bioeconomy Research)	Education	Joint program for PHD course "Importance of wood performance, protection, and longevity in the presence of climate change" coordinated by E.Kuka to be held before conference WSE 2026 15-16 September 2026, Riga, Latvia	06.2025.-12.2025.
6	Baltic International Centre for Economic Policy Studies	Joint project application	Latvian Council of Science project "The potential of non-timber forest products: Linking forest-based bioeconomy with social and cultural aspects - lzp-2025/1-0478"	09.2024-04.2025
7	Central Europe partners (EL, IT, AT, PL, CY, ES, LV, RO, BE, FR)	Join project application	"A thematic network to bloom the farmers' income by innovative agricultural systems for arable crops and by the circular use of their agricultural residues" HORIZON-CL6-2025-03-GOVERNANCE-12	07.2025-09.2025.
8	Thermory AS, Ošukalns Ltd, Niedrāji Ltd, Stiga RM Ltd	Plywood thermal modification	interest in the nitrogen-based wood TM method	09.2024.-12.2025.
9	Baltic Biomaterial Centre	Cell compatibility analysis	Results on cell compatibility	07.2024.-10.2025.
10	Latvijas Finieris	Veneer cores, chips and birch bark	Research raw material	09.2024.-11.2025.
11	Kronospan Latvia	Resources (recycled wood particles);	Delivered recycled wood particles used in the study; information exchange about the project results	09.2024.-12.2025.
12	**LBTU**, Latvia	Consultation and information exchange	Obtained knowledge about production of CWM and sawdust used in the study	09.2024.-12.2025.
13	National Research Council of Italy - Institute of Bioeconomy	Reserch	Manuscripts	09.2024.-12.2025.
14	"ARB POPE" Ltd.	Preparations of the samples	Testing results	10.2025.-12.2025.

15	"AmberBirch"Ltd.	Interest in research results	Future research cooperations	11.2025.-12.2025.
16	"Cross Timber Systems" company	Voluntary	Pine waste is used as a filler in a new WPC	09.2024.-12.2025.

2.2. Impact of the project on the students within the context of their study process, creating internship and employment opportunities, as well as platforms and the use of the scientific outcomes of the project in the process of attaining university degrees.

In the **WP1** the research has been directly integrated into doctoral education, with results incorporated into Raitis Rieksts-Riekstiņs' PhD on Scots pine growth and resistance (Lithuanian Research Centre for Agriculture and Forestry) and contributing to Karlis Dumiņš and Viktorija Vendina's doctoral thesis compilations. Students were actively involved in laboratory work, including DNA extraction and genotyping of pine nurseries and wild stands, providing practical employment and research experience. Two bachelor students in 2025 studied forest stand management and the impact of Ips typographus on spruce mortality.

Education materials were updated and expanded for joint courses with Linnaeus University, including the "International Sustainable Small-scale Forestry I" program, and for a Baltic and Nordic doctoral course scheduled in September 2026, fostering regional and international collaboration. The developed FTIR methodology has been transferred to the H2020 Alfawetlands project, broadening research applications and offering students internship opportunities. High-level regional publications are being drafted, providing platforms for students to disseminate results, enhance professional competitiveness, and strengthen scientific visibility. Overall, the activities significantly enhanced education, skills development, and student engagement across multiple academic levels.

During **WP2** activities, education materials were updated for joint courses with Linnaeus University, including the "International Sustainable Small-scale Forestry I" lifelong learning course for forest owners. A new programme was also developed with Latvian and Norwegian partners for Baltic and Nordic doctoral courses scheduled for September 2026, enhancing regional academic collaboration.

WP3 provided a strong platform for student involvement across all study levels. Students participated in laboratory work, material testing, data analysis, prototype development and LCA training. The doctoral thesis "Properties and the possibilities for improvement of pine (Pinus sylvestris L.) cellular wood material performance" was defended and the doctoral thesis "Investigation of thermally modified birch, aspen, and poplar veneers for the production of more environmentally friendly plywood" was submitted for the start of the promotion process.

3 PhD thesis defended; **1 -** completed and submitted to Council, **4** – are being developed. **1 MSc** thesis defended; **1-** is being developed. **3 BSc** thesis defended; **3** - are being developed. Students also achieved 2nd place in the national BISC-E competition with a project based on WP3 results.

Table 2

Doctoral, master's and bachelor's theses supervised or advised by the project manager or principal investigators within the scope of this project (if defended, indicate this in the last section of the table, supplementing with the date and the relevant doctorate council)				
No	**Author**	**Title of the thesis, level of study, hyperlink to the doctoral / final theses database**	**Supervisor and/or consultant**	**Defence (planned defence)**
1	R.Matisons	**PhD**, Ecological plasticity of responses of radial increment of scots pine and its potential for breeding; https://doi.org/10.22616/lbtuthesis/2024.013	Ā.Jansons	26.11.2024
2	P.Zeltiņš	**PhD**, Comparative growth modelling of genetically improved Norway spruce, Scots pine and silver birch forest stands, ISBN 978-9916-91-023-8; https://doi.org/10.15159/emu.155	A.Kangur	30.05.2025

3	J.Iejavs	**PhD**, Properties and the possibilities for improvement of pine (*Pinus sylvestris* L.) cellular wood material performance, *https://lbtufb.lbtu.lv/dissertation-summary/woodworking/Janis_Iejavs_Promocijas_darba_kopsavilkums_2025_LBTU.pdf*	U.Spulle	10.10.2025.
4	A.Meija	**PhD**, Investigation of thermally modified birch, aspen, and poplar veneers for the production of more environmentally friendly plywood, *Thesis in Dec.2025 are submitted to Promotional Council.*	U.Spulle	(June 2026.)
5	K. Dumins	**PhD**, Development of various types of commercially valuable tree species plant material depending on soil preparation method	D.Lazdina	(2027.)
6	V.Vendina	**PhD**, Recultivation of mining sites in Zemgales region by establishing of pine (*Pinus sylvestris* L.) forest	D.Lazdina	(2027.)
7	G.Šnepsts	**PhD**, Model for prediction of wind damages in Norway spruce stand	Ā.Jansons, J.Jansons	(2027.)
8	G.Sosins	**PhD**, Wood properties after thermal modification in nitrogen environment at elevated pressure	J.Grinins	(2028.)
9	V.Kudrjavceva	**MSc**, Isolation of soda lignin from wood waste and its physicochemical characterization. *https://dspace.lu.lv/handle/7/69945*	G.Shulga	05.06.2025.
10	K.Radovska	**MSc**, Glycerine-based sustainable extraction of bioactive compounds from tree bark for transdermal use.	M.Lauberts	(June 2026)
11	A.Troika	**BSc**, The threat of the spruce bark beetle (*Ips typographus L.*) to unproductive and productive Norway spruce:	A. Šmits, O.Zaļkalns	06.06.2025.
12	E.Luka-Indrāne	**BSc**, Evaluation of the effectiveness of spruce bark beetle (*Ips typographus L.)* pheromone traps on adjacent spruce stands.	A.Šmits, I.Straupe	06.06.2025.
13	R.Zabarovska	**BSc**, Changes in pine wood across the stem diameter.	D.Cīrule	04.06.2025.
14	A. Vjalikova	**BSc**, The effect of temperature on the yield and composition of pine bark extractives isolated by pressurized water treatment.	M.Pals	(June 2026)
15	I.Sutris	**BSc**, Production of *Phlebiopsis gigantea* spores (oidia).	O.Grigs	(June 2026)
16	E.Vahere-Abražune	**BSc**, Biotechnological approach to the development of a biological plant protection product for forestry.	O.Grigs	(June 2026)

2.3. Impact of the project and its outcomes on policy makers and policy implementers in the sector, providing recommendations for developing sector policy

Under **WP1**, the research has made a substantial impact on adaptive forest management by promoting the liberalization of tree breeding programmes through assisted gene transfer, increasing genetic variation in managed Scots pine stands. The results provide critical guidance for agile adjustments in seed source use under intensive forestry, helping reconcile timber production with nature conservation requirements under recent EU legislation, while clarifying regional forestry practices and supporting national bioeconomy. WP1 also strengthened policy implementation through the development of a cost-effective, accredited FTIR methodology, aligned with the EU Soil Monitoring Directive. This rapid screening tool enables large-scale assessment of soil health and nutrient status, supporting evidence-based decision-making for sustainable forest management and informing national soil and forest health monitoring programmes. Furthermore, knowledge generated under WP1 informed practical interventions, including amendments to salvage logging regulations during Ips typographs outbreaks, ensuring forest resilience and pest control measures are science-based. Collectively, WP1 demonstrates high impact by linking research outputs to policy, operational forestry, and innovative monitoring

technologies, enhancing sustainable management, regulatory compliance, and long-term forest ecosystem resilience.e, and long-term forest ecosystem resilience.

Activities performed within **WP2** were finalized with the development of three forest management scenarios and the draft of definition of key elements to be used as indicators for performance measurement in the identification and classification of sustainable forest and land management practices. In addition, guidelines for the evaluation of ecosystem services in Latvia were developed.

WP3 results were presented to the Latvian Forest Industry Federation, supporting discussions on greener production practices, sustainable construction materials, and circular bioeconomy pathways. The development of a local biological stump-treatment agent contributes to forest-health policy and reduces dependence on imported biological products. The demonstrated potential of bark extractives for composite materials supports policy directions promoting higher-value use of forest residues and reduced reliance on fossil-based additives.

Table 3

No.	In cooperation with	Type of cooperation	Outcome	Time period
1	Ministry of agriculture	consultations	Scenarios for forest management	09.2024.-12.2025.
2	NGO Latvian forest owner association	Joint event	Key elements to include in forest management scenario modelling.	04.2025.-06.2025.
3	State Forest Service	Legislation on forest pest management (*Ips typographus, Ips acuminatus*)	Recommendations to be implemented in Regulations of the Cabinet of Ministers.	2024-2025.
4	University of Life Sciences and Technologies	Drafting of Key performance indicators for forest management	First draft of Recommendations (guidelines) for companies to assess key performance indicators for impact analysis and reporting on on identification and classification of sustainable forest and land management in Latvian)	09.2024-12.2025.
5	Latvian Forest Industry Federation	Interest in research results	Dissemination of research results – companies' level	09.2025.-12.2025.

2.4. Impact of the project and its outcomes on society as a whole, through knowledge transfer and awareness raising of the role of research and contribution thereof to society.

Under **WP1**, the research significantly enhanced the efficiency of forest breeding, contributing to the long-term sustainability of managed forests, which represent up to 16 % of GDP and affect overall economic activity and societal welfare. The results provide a robust, science-based resource for education on forest management's effects on genetic diversity, supporting strategies that improve resilience without compromising local genetic values. WP1 also developed an FTIR-based diagnostic solution, enabling knowledge transfer through digital outreach, international conferences, and research project applications, offering cost-effective alternatives to traditional methods. This approach ensures broad societal access to scientific results via open-access proceedings and networks, demonstrating how predictive modeling optimizes soil amendment strategies and promotes circular economy principles through evidence-based resource management. Additionally, WP1 facilitated extensive dissemination through mass media, educating the public and forest owners on environmentally friendly practices, pest management, and sustainable decision-making. Collectively, WP1 highlights the societal, economic, and ecological impact of advanced forest research, linking cutting-edge diagnostics, education, and management strategies to resilient, sustainable forestry.

WP2 activities were primarily disseminated through the **Silava** website and social media channels. The results were further popularized at the final conference and at a thematic seminar organized within the research programme in

cooperation with the Latvian Forest Owners' Association. A podcast episode on "Use of harvester production data in forestry decision-making and the assessment of sustainability indicators" was subtitled in English. Cooperation between JSC Latvian State Forests and Latvijas Finieris with **Silava** and **LSIWC** within the Bioeconomy School, targeting secondary school students.

WP3 results were disseminated widely through Scientific Night 2025, "Biltim Tehnika" 2025 exhibition, national television, project opening and closing conferences, institutional websites and social media, public lectures and career-day events. Demonstrations of SA-bonded particleboards, WPCs, TM veneers and fungal biocontrol technologies increased public awareness of sustainable wood innovations and the societal value of research.

Table 4

No.	Communication channel (e.g., radio, TV, social networks, etc.)	Activity (interview, popular science article, seminar, etc.)	Target audience planned / reached (describe the target audience and the size of the audience reached)	Available (hyperlink)	Date of publication / event
1	**Forest4LV** LinkedIn page	Article / post	Fellow researchers and scientists, forest industry, students, general public	https://www.linkedin.com/showcase/forest4lv/?viewAsMember=true	09.2024.-12.2025.
2	**LSIWC** homepage	Article / post		https://kki.lv/zinatniska-darbiba/projekti/forest4lv; https://kki.lv/aktualitates	09.2024.-12.2025.
3	**LSIWC** Facebook page	Article / post		https://www.facebook.com/kki.lv	09.2024.-12.2025.
4	**Silava** homepage	Article / post		https://www.silava.lv/petniecība/petijumi/Forest4LV	09.2024.-12.2025.
5	**LBTU** homepage	Article / post		https://www.lbtu.lv/lv/projekti/apstiprinatie-projekti/2024/inovacijas-meza-apsaimniekosana-un-koksnes-apstrades	09.2024.-12.2025.
6	Project opening and closing conference	Conference		https://kki.lv/aktualitates/valsts-petijumu-programmas-forest4lv-atklasanas-konference-latvijas-valsts-koksnes-kimijas-instituta, https://www.youtube.com/watch?v=upJtn0BnfMY	08.11.2024., 10.12.2025.
7	TV	Interview in the National television (LTV)	General public	https://replay.lsm.lv/lv/skaties/ieraksts/ltv/367925/dienas-zinas (see from 26:00)	10.12.2025.
8	Lecture	Given lecture to students at Valmiera Vocational Education and Training Centre on biomass valorisation products and	Students, around 100 in attendance	https://valmierastehnikums.lv/valmieras-tehnikuma-viesojas-latvijas-valsts-koksnes-kimijas-instituta-petnieki-un-fibenol-parstavji/	24.02.2025

		presentation of Lignin Chemistry Laboratory activities including given activity.			
9	Public event	Participation in Riga technical University organized "Career Day 2025". Presentation information related Lignin Chemistry Laboratory activities including given activity.	Students, reached around 250 students.	https://www.rtu.lv/lv/studentuserviss/karjeras-centrs-ssc/karjeras-diena	14.03.2025
10	Public event	Participation in event "Researchers Night 2025"	General public, around 370 in attendance	https://kki.lv/aktualitates/zinatnieku-nakts-2025-atklaj-sevi-petnieka-genu	26.09.2025
11	TV	Interview in the National Latvian and Polish television	Whole Latvia and Poland	https://kki.lv/en/latest-news/lsiwcs-wood-bone-implant-research-featured-polish-national-television	15.04.2025.
12	Radio	Interview in the National Latvian radio	General public	https://kki.lv/en/latest-news/bone-implants-made-wood-latvian-researchers-seek-alternatives-titanium	14.04.2025.
13	Biltim Tehnika 2025	Exhibition	General public	https://kki.lv/en/latest-news/bioengineering-laboratory-participates-exhibition-biltim-technika-2025	24–26. 09.2025
14	Project "Engineering Start: Choose, Explore, Discover"	**LBTU** Lifelong Learning Center implemented the project	Introducing secondary school students from all regions of Latvia	https://www.lbtu.lv/en/article/2025-04-30/lbtu-lifelong-learning-centre-continues-project-engineer-s-start-discover	2025

2.5. Scientific results of the project and ensuring access thereto

The research under **WP1, Task1.1** resulted in numerous high-quality publications and manuscripts addressing tree growth responses to climatic conditions, the role of retrotransposons in stress responses, and genetic controls on increment, several of which were presented at international conferences, including Eurodendro2025. Sustainability of breeding effects following thinning was evaluated, and the influence of Scots pine plantations on forest genetic diversity was assessed, with findings prepared for submission to leading journals. Additional manuscripts on modulating effects of management practices and sensitivity analyses were drafted, with results already shared at high-level scientific meetings, demonstrating the strong dissemination and visibility of WP1 outputs.

Task1.2: The effectiveness of mechanised direct seeding using improved Scots pine material was confirmed, providing a cost-effective approach to transferring genetic gains from breeding programs into large-scale forest regeneration. This work produced two published articles and one manuscript submitted, with practical applicability for state-managed and

private forests in Latvia. Extensive sample plot networks for continuous canopy forestry and TREMs were established, analysed, and published or presented at conferences, generating robust data for stand management. Automated image recognition models were calibrated and verified, facilitating post-harvest monitoring. FTIR-based methodologies were developed for soil and foliage assessment, presented in international conferences, integrated into predictive models, and applied in forest management scenarios. Additional studies on drainage systems, site-specific growth responses, and climate sensitivity generated two open-access publications and ongoing manuscripts.

Task1.3: Growth responses to non-lethal fire, Ips pest damage, and ungulate impacts on young Scots pine were evaluated, producing three peer-reviewed publications and several conference presentations, directly informing adaptive management practices and forest protection strategies.

Task1.4: Ecological assessments of epixylic moss and deadwood age distributions were published, supporting evidence-based conservation and highlighting the importance of scientifically grounded species lists and habitat connectivity under different management regimes.

Overall, **WP1** demonstrates high scientific productivity and societal impact, with extensive publication outputs, conference visibility, and applied results supporting sustainable forest management, policy development, and advanced research capacity in Latvia and the wider region.

WP2 was not primarily focused on scientific research activities, but rather on the integration of results from WP1 and WP3 into decision-making processes and modelling applications. Nevertheless, scientific capacity building was achieved through participation in four international conferences, where four presentations were delivered (excluding the final conference plenary presentation). These contributions addressed forest management, the socio-economic impacts of selected management scenarios, and education and capacity building within the forest sector.

WP3 produced a substantial body of scientific outputs:

- Product (8) and technology (5) prototypes,
- Pilot-scale demonstration of *P. gigantea* spore production,
- 5 open-access datasets (Zenodo) (pine JW, birch JW, PU foams):
    - Pine - http://doi.org/10.5281/zenodo.17659785;
    - Birch - http://doi.org/10.5281/zenodo.17659931;
    - Rigid polyurethane foams – https://zenodo.org/records/17986282;
    - Particleboards from longitudinal sawdust - https://zenodo.org/records/18377099;
    - Particleboards from recycled wood particles - https://zenodo.org/records/18350472.
- 13 conference presentations or posters (WSE 2025, Baltic Polymer Symposium 2025, RRB 2025, IOCM2025),
- 14 Q1–Q3 journal publications,
- an app for rapid analysis of hardwood anatomical structure,
- 2 recommendations for sectoral participants (biorefinery and bio-based building materials):
    - D3.3. Recommendations on the usage of wood-based materials in furniture and construction elements;
    - D.3.4. Recommendations on the usage of wood processing residues to produce added value biobased materials.

All scientific results are summarized in deliverables (product and technology prototypes, datasets, publications, recommendations and other - https://failiem.lv/u/m3y6mast7r) highlighting complete circular bioeconomy cycle, which demonstrates that Latvia's forestry resources can be utilized comprehensively – from the use of primary wood in construction and furniture to the conversion of by-products into green chemistry products, ecological binders, polymers, and medical materials.

3 Implementation

WP1 A.1.1.1 The activity was implemented according to the planned and has currently exceeded the intended results. The activity was implemented in collaboration with colleagues form Lithuania and Romania, thus facilitating international recognition and collaboration. Doctoral and underaged students from implementing institutions were

involved in most of the stages of activity. Initially, the planned schedule slightly shifted to harness the collaboration opportunity, which aided comparison of populations sensitivity across extended climatic gradients, thereafter the effects of productivity were estimated. ***A.1.1.2.*** The activity was implemented in **Silava** via horizontal collaboration between forest genetic laboratory and Adaptation and breeding departments (groups). As intended, previously gathered data were gathered, systematized, and reanalysed in contemporary manner. Staff of different backgrounds, as well as students were involved in the endeavour. The attendance of conferences allowed finetuning of the results for preparation of the manuscript, while increasing the recognition of researchers. The activity was implemented according to the initial plan, although some fine adjustments in methodologies were implemented promptly. ***A.1.2.1.*** Scots pine stands renewed by direct sowing were assessed and genotyped using a highly informative panel of SSR markers. In addition, the seed orchard clones from which the seeds were genotyped, allowing assignment of parentage. On average, 87% of the analysed seedlings were assigned to maternal genotypes from the Salaca seed orchard, and this proportion was similar across all four forest stands. Research activities and core results Four forest stands in eastern Latvia, regenerated by mechanised seeding using seeds from the Salaca seed plantation in spring 2014, were analysed. Stand development was assessed in the seventh growing season after sowing by measuring seedling height and root collar diameter. 367 seedlings were genotyped using 16 microsatellite (SSR) markers, as well as 109 clones from the Salaca seed plantation Maternal assignment was performed to determine the proportion of seedlings originating from the Salaca seed orchard, as well as relatedness and genetic differentiation (Fst) analyses. Seedlings derived from seed plantation seeds had higher growth indices after 5 years, compared to seedlings that were established from seeds derived from surrounding pine stands, however these differences were not statistically significant. ***A.1.2.8.*** The project advances the field of forest diagnostics by introducing a novel FTIR spectroscopy methodology that captures complex soil – biomass interactions more effectively than traditional direct nutrient measurements. This innovation enhances the international competitiveness, as demonstrated by the dissemination of these findings in scientific conferences and publication in indexed proceedings. Additionally, the rigorous validation and upcoming accreditation of this method with the Latvian National Accreditation Bureau (LATAK) significantly strengthens the technical capacity and quality assurance standards of the local research community.

All planned activities of **WP2** were implemented in accordance with the original work plan. Minor adjustments to the timeline were required due to scheduling and organizational considerations; however, these did not affect the scope, objectives, or quality of the planned outputs and results. A preparatory meeting was held with the Ministry of Agriculture to discuss cooperation frameworks and the content-related outcomes of the three modeled forest management scenarios, supporting alignment between research results and policy needs. (16 April 2025) A seminar was organized in cooperation with Latvian private forest owners association, focusing on sustainable forest management practices and the application of research-based knowledge in practical forest management. (24–25 April 2025) A structured discussion with policy and decision-makers was conducted to present interim research results and to evaluate their implications for forest management strategies and forest-based bioeconomy development. (2 May 2025) Data were collected to refine and improve forest growth and socio-economic models. During this phase, ecosystem service valuation criteria were defined, key performance indicators were selected and applied, and calculations for three alternative forest management scenarios were expanded. The results formed the basis for subsequent scientific analyses, conference presentations, and publications. (started at May and continued during all project period 2025). A thematic workshop was held to discuss cooperation between LNU, **LBTU**, and **Silava** in student training, integrating **Forest4LV** research results into higher education curricula. On the same date, a presentation entitled “Scaling Up Socioeconomic Benefits in the **Forest4LV** Research Programme” was delivered at the Conference of Life-Long Learning for Sustainable Forestry in Salaspils, Latvia. (16 June 2025) Academic cooperation with Linnaeus University (Sweden) and **LBTU** continued through the study course “International Sustainable Small-scale Forestry I”. Teaching materials were piloted during the 2025 academic year using the Canvas learning environment and prepared for further use in 2026. In parallel, planning of a Nordic–Baltic PhD course in cooperation with the Institute of Wood Chemistry was initiated “Importance of wood performance, protection, and longevity in the presence of climate change”. (Throughout 2025 to be held in 2026.09.14.) At the Nordic-Baltic Forest Growth and Yield Conference in Tartu, Estonia, a presentation entitled “Approaches used in forest growth and yield model ‘AGM’ for forest resource assessment under different management regimes in Latvia” was delivered, highlighting methodological approaches for assessing forest resources under alternative management

regimes. (26–28 August 2025) At the 12th International Scientific Conference "RURAL DEVELOPMENT 2025: Resilience to Global Change" in Kaunas, Lithuania, a presentation titled "**Forest4LV**: advancing interdisciplinary capacity and bioeconomic innovation in Latvian forest research" emphasized interdisciplinary collaboration and innovation in forest bioeconomy research. (1–3 October 2025) A poster presentation entitled "Long-term socio-economic impacts of scenarios of restrictions on the management of commercial pine forests" presented results from scenario-based modeling, illustrating long-term socio-economic impacts of management restrictions on commercial pine forests. (November 2025) Project development and funding activities resulted in the approval of the national FLPP project No. lzp-2025/1-0478 "Potential of Non-Wood Forest Products: Linking Forest Bioeconomy with Social and Cultural Aspects" and the HORIZON-CL6-2025-03 BloomEra project, while the HORIZON-JU-CBE-2024-CSA-01 CIRCUIT proposal was placed on the waiting list. (2025).

WP3 was implemented through coordinated experimental work across **LSIWC**, **LBTU** and **Silava**, supported by industrial partners. To develop the innovative technologies and evaluate them to produce competitive and sustainable products using local forest resources and to promote the rational use of wood, two types of feedstock was investigated in the WP3 on the basis of the most common wood species in Latvia - pine and birch (in some tasks also alder and aspen): 1) Residues form sawing of pine timber and/or WCM production – sawdust (50%) and bark (10-20%); 2) Residues from birch plywood production – veneer chips (up to 40%), veneer peeler core (6%) and bark (10-20%).

Task 3.1 The technologies and products to expand the use of wood-based materials in construction in line with the EGD. To achieve objectives of the **T.3.1.** the evaluation of juvenile wood (JW) in glued wood products, as well as thermo-modification (TM) of veneers to improve the plywood weathering properties were investigated. Activity **A.3.1.1.** investigated the JW of pine (*Pinus sylvestris L.*) and birch (*Betula spp.)* focusing on the technological possibilities of its use. Wood samples were obtained from the forest thinning (in cooperation with **Silava**) and the plywood industry as veneer peeling cores. In the project, JW parameters were analyzed which affected the JW interaction with adhesives and glued product application: anatomical characteristics, chemical composition (incl. extractives), physical and strength properties (interaction with moisture and water, buffer capacity, bio-durability, etc.). Given the limited duration of the project, a feasibility study was carried out regarding the gluing of JW, clarifying the characteristics of the glued products, the suitable types of glues, and the output technological data. Preliminary data were obtained for the development of life cycle assessment (LCA) of JW products in the course of future projects.

Several wood TM methods were evaluated to obtain plywood from veneers modified in nitrogen and vacuum atmosphere. The impact of TM on the aspen (*Populus tremula*) and black alder (*Alnus glutinosa*) wood physical and mechanical properties, biological durability and weathering performance were evaluated in the **A.3.1.2.** While LBTU in **A.3.1.3.** used birch (*Betula pendula Roth.),* aspen (*Populus tremula L.)* and poplar (*Populus x canadensis Moench*.) veneers obtained by vacuum TM in cooperation with project scientific institution partner - Italian Institute of BioEconomy (IBE). Bio-adhesive – birch bark processing product suberinic acids was used to bond the thermo-modified veneers (**A.3.2.3**.). The plywood gluing parameters were clarified (adhesive consumption, pressing time etc.). The gluing quality, strength and other properties of the obtained plywood were tested. In order to compare the environmental impact of the obtained plywood during the entire product life cycle with traditional birch plywood, a LCA was carried out.

Task 3.2 Biorefining technologies for the integrated use of forest resources to produce higher value added products. To integrate forestry and wood processing residues as a feedstock in sustainable biorefining technologies to obtain high added value products several feedstock and target products were investigated. All types of woody by-products were covered: 1) hardwood forestry or plywood residues (birch as reference material); 2) bark of common wood species (pine); 3) pine wood sawdust after sawing of timber and/or from CWM production residues, which make up about 46% of the log. In **A.3.2.1.** the catalytic pretreatment technology of plywood residues was carried out to obtain 5-furfural, acetic acid and hydroxymethylfurfural (5-HMF). The proposed solution involved two stages: 1) birch wood catalytic hydrothermal pretreatment to selectively separate the hemicellulose portion and convert it into furfural (a product imported into the EU), thereby gaining better access to the cellulose part for its transformation into 5-HMF; 2) catalytic treatment of the lignocellulosic residue in the organic solvent environment. By integrating these two processes, the opportunity arises to utilize 60-70% of the birch wood processing byproduct stream in the plywood production plant. In **A.3.2.2.** processing of birch and pine barks into catechol-moiety bearing extractives were carried out. Hot solvent extraction of alder, birch, and pine bark, obtained from **Silava** (WP1), was performed using glycerol and glycerol-water

mixtures. The extraction conditions (solid/liquid ratio, temperature, pressure, number of extraction cycles, etc.) were optimized using response surface modeling. Catechol-moiety-bearing compounds were absorbed onto appropriate resins, such as Amberlite XAD-2 for oregonin, and then desorbed using a glycerol-water mixture as the solvent to obtain the final product. The antimicrobial activity of extractives and wound dressing films incorporated with bark glycerol extracts were tested using broth dilution assay and direct contact assay. In **A.3.2.3.** pine wood sawdust (filler) and ecological binder (from birch bark) were used to obtain ecological wood-based composites. Replacing synthetic binders with ecological ones from birch bark solve several problems affecting both human health, environmental pollution, and utilization aspects. By adapting the developed ecological binder to individual wood species, including pine wood, several technological aspects were tested (pressing temperature, duration, binder amount, physical-mechanical properties of the boards). This increases the flexibility of the developed technology, its TRL and competitiveness, moving towards the transfer of the technology at the industrial level. Developed new particleboard products were compared with similar products on the market by testing its physical mechanical properties according to current standards and evaluating their suitability for furniture constructions.

Task 3.3 Use of wood processing and wood biorefinery residues for the production of polymer composites and insulation materials. To solve the problems of using wood processing residues to obtain bio-based polymer composites and insulation materials, several biomass processing by-products were chosen as a feedstock - bark extraction residue from **A.3.2.2.**, wood mechanical processing residues, as well as pulp production residue from pine wood (tall oil). These residues were investigated to obtain several polymer products for insulation (bio-based rigid PU foams) and for increasingly popular interior materials (wood polymer composites - WPC) to increase their added value and substitute the petrochemical part with biobased compounds. The aim of **A.3.3.1.** was to leverage the benefits of both suberinic acid-based polyols and tall oil-based polyols to develop rigid polyurethane (PUR) foams with enhanced thermal stability and reduced flammability (TRL 6). To achieve this, suberin depolymerization technology was adjusted to produce three different suberinic acids (SA) with various polyphenol contents. Respective SA-based polyols were synthesized. Tall oil-based polyols were used to lower the viscosity of the polyol systems. Additionally, more sustainable alternatives to Tris chloroisopropyl phosphate (TCPP), e.g. ammonium polyphosphate, triethyl phosphate, and graphite, were explored for the PUR foam formulation to reach appropriate flammability properties.

In **A.3.3.2** methods for isolating carbohydrate-enriched fractions from extracted pine bark (**A.3.2.2.)** through hydrothermal treatment using a high-pressure PARR reactor were developed. The component and functional compositions of the extractives were studied using GC, HPLC, and wet chemistry methods. Oxypropylation was performed at 150-170°C and ambient pressure, with FTIR spectroscopy used to monitor the reaction. GPC and wet chemistry methods were characterized for the obtained polyols, which was introduced into PUR foam recipes as substitutes of commercial fossil-derived polyol polyethers. The remaining bark fraction was used as a filler in the PU foam composition. The compression characteristics, dimensional and thermal stability, closed cell content, and thermal conductivity of the PUR foams with a high content of renewables were studied.

In **A.3.3.3.** targeted and scientifically-based improved physicochemical functionalization of pine wood residue (T.3.5.) was tested to control the compatibility and regulate the interaction between the pine filler and polymer matrix in the wood polymer composite (WPC), intended for production of WPC for building interior design. The WPC was made from recycled polypropylene as a polymer matrix and functionalized pine sawdust with the addition of biological additives obtained from wood biorefining. The WPC processing parameters (processing temperature and time, screw velocity, torque, injection molding pressure) were determined and the properties of the WPC (mechanical, including impact viscosity, dimensional stability, wettability, thermostability) were investigated. The final formulation of the WPC was selected, characterized by its mechanical properties.

Task 3.4 Original solutions for innovative products based on logging by-products and non-wood materials. In the task there two completely different research fields using different wood processing residues (birch veneer peeling core and pine wood residues) were investigated. In **A.3.4.1.** densification of chemically pretreated wood into the osteosynthesis implant material (medicine) was investigated. Improvement of the birch wood (veneer peeling core) properties, increased biocompatibility and reduced swelling were implemented by the sequential 4-step treatment method - partial delignification using the soda process, followed by extraction, chitosan-impregnation and thermal densification of the solid wood. Biomechanics and implant stability in bone was studied in a specially designed test facility already owned by LSIWC. As a result, new product prototype and technology were developed. In **A.3.4.2.** the P. gigantea spore

production on pine residues (from **T.3.5**.) was investigated to be used in forestry practices to reduce root and butt rot caused by the fungus Heterobasidion in coniferous stands in WP1. In 2023, LSIWC and Silava signed a License agreement (agreement no. 2023/56e-IP/LIC) for intellectual property "Biologic preparation for stem protection against Heterobasidion spp. spore infection and isolate suspension mixture obtainment method" use, envisioning rights for Phlebiopsis gigantea isolate PG 182 un PG 382 production up-scale research. As a result P. gigantea biological control agent pilot batch of 50 L was produced and technology description developed.

Task 3.5 Increasing the efficiency and accuracy of the use of wood resources, smart technology solutions. Cellular wood material (CWM) and Lightweight Stabilized Blockboard (LSB) have a lack of detailed and comprehensive information about the properties for potential manufacturers to create a declaration of product conformity. Part of the clarification of these characteristics was carried out in this task. In **A.3.5.1.** the CWM was manufactured according to the standard requirements and selected properties of CWM and structural element was tested (incl. physical-mechanical characteristics, acoustic properties, combination of smart technology materials). In **A.3.5.2.** the LSB building elements (doors, walls etc.) were calculated in order to carry out its successful implementation. Smart technology parameters (cutting speed, resistance, energy consumption etc.) were approved and the technological and operational characteristics of LSB were determined (dimensional stability (i.e., shrinking-swelling), etc.). CWM and LSB materials were tested in combination with thermomodified veneers from **A.3.1.3** and were evaluated to respond to the Circular economy requirements approved by LBTU. In addition, the residues from the production of the CWM were used as feedstock in **A.3.2.3., A.3.3.3. and A.3.4.2.** to evaluate the increase of the added value.

Activities included:

- Anatomical, chemical and physical characterization of birch and pine juvenile wood for gluing,
- Thermally modified wood (bulk and veneers) trials under nitrogen and vacuum,
- Biorefinery extractions (suberinic acids, catechol extractives, 5-HMF),
- Bio-based polyol synthesis and rigid PU foam production,
- Wood polymer composite formulation and extrusion,
- Composite development using functionalized bark extractives,
- Particleboard pressing using suberinic acids as binder,
- Densification of veneer cores for medical applications - osteoimplants,
- Solid-state fungal cultivation at pilot scale,
- LCA training and integration into plywood development,
- Testing of lightweight CWM and LSB materials.

WP3 played a central role in advancing the programme's scientific and technological ambitions by integrating forestry, wood chemistry, materials science, and industrial engineering into a coherent innovation pipeline. The work package not only demonstrated the feasibility of multiple high-value biorefining pathways but also delivered tangible progress toward industrial deployment, raising the technological readiness of several solutions (ecological binders, bio-based polyols, rigid PU foams, WPC formulations, platform chemicals, extractives, thermally modified wood and fungal biocontrol agents). The coordinated collaboration between **LSIWC, LBTU, Silava**, and industry partners ensured that laboratory-scale discoveries were systematically translated into scalable prototypes, validated through mechanical, chemical, biological, and environmental performance testing. By valorising diverse wood and bark residues, WP3 significantly strengthened Latvia's capacity to produce competitive, sustainable, and circular bio-based materials, directly supporting national bioeconomy priorities and EU Green Deal objectives. The comprehensive experimental results, new product prototypes, and established technological workflows form a robust foundation for future commercialization, patenting activities, and international research cooperation. All deliverables were completed within the project timeframe, and WP3 fully achieved the objectives defined in the project proposal.

WP4 Coordination and Management. The **Forest4LV** project was coordinated by **LSIWC**, and its implementation followed a structured and collaborative management model. A project **Kick-off meeting** launched the activities, after which **in-person Project Reporting Seminars** were held every four months, each time hosted by a different partner institution. During these seminars, all **Task and Activity leaders** presented progress, upcoming work plans, identified risks, and discussed methodological adjustments. These meetings consistently fostered constructive dialogue, enabling partners to identify complementarities between activities and strengthen cross-institutional cooperation. Each seminar

concluded with a guided visit to the host institution's research infrastructure, further enhancing mutual understanding of available capacities and opportunities for collaboration.

To mark the completion of the programme, a **Final Conference** was organized in December 2025, jointly with the State Research Programme **GreenAgroRes**. The event brought together representatives from government institutions, industry, and the scientific community, providing a platform to present the programme's results, discuss their implications for the forest sector and bioeconomy, and highlight the long-term value of the interdisciplinary cooperation established through Forest4LV.

WP5 Exploitation and Dissemination ensured that the scientific, technological, and policy-relevant results generated across the **Forest4LV** programme were systematically communicated, transferred, and made accessible to stakeholders in Latvia and internationally. This work package played a central role in transforming research outputs into practical value by coordinating publications, conference participation, prototype demonstrations, policy recommendations, and public-facing communication activities. All actions implemented under WP5 are reflected in **Table 4 and in the Annex** of this report (summary available at: https://failiem.lv/u/m3y6mast7r).

Through WP5, partners ensured that **Forest4LV results reached diverse audiences** - from policymakers and industry representatives to academic communities, forest managers, and the general public. The work package supported the preparation of high-impact scientific publications, facilitated participation in national and international conferences, and promoted the visibility of newly developed technologies and prototypes. It also strengthened the programme's contribution to evidence-based policymaking by preparing targeted recommendations and by engaging with ministries, agencies, and sectoral organisations.

All results (Deliverables) achieved **in Forest4LV** are summarized in the following table:

WP	Task	Articles Q1/Q2	Other articles	Conferences	Product prototype	Technology prototype	Recommendations for policy makers	Recommendations (other)	Data sets	Dr. thesis	Other*
WP1	T.1.1	20	11	38			2	2	2	2	9
	T.1.2					1					
	T.1.3										
	T.1.4										
WP2							3	1	2		6
WP3	T.3.1	12				1		2	1	1	29
	T.3.2				2	2			2		
	T.3.3				3				1		
	T.3.4				2	2			1		
	T.3.5		2		1		1			1	
WP4											2
WP5											65
Total		**32**	**13**	**38**	**8**	**6**	**6**	**5**	**9**	**4**	**>67**
Planned		**19**	**12**	**22**	**8**	**6**	**6**	**5**	**7**	**4**	**111**
Extra results		**13**	**1**	**16**	**0**	**0**	**0**	**0**	**2**	**0**	**44**