**Table 1**. Main types of bio-based products

| **Biomaterials by category** | **Type of bio-based products** | **References** |
| --- | --- | --- |
| **Category 1**  Binding materials, aggregates and/or additives for soil, cement and/or concrete | Sustainable cement  Green, ecological and/or sustainable concrete  Concrete blocks  Hardened concrete  Agro-concrete/cement  Ordinary Portland cement (OPC) concrete  Lightweight aggregate concrete  Cement concrete  Geopolymer concrete  Clayey sand and soil  Cement mortars  Activated cement mortar  Cement-based panels  Wood-cement blocks  Roofing tiles  Clay and laterite soils | [7, 18, 54, 56, 63, 67–70, 72, 73, 76, 22, 82, 84, 87, 89–91, 93, 100, 23, 27, 36–38, 52, 53] |
| **Category 2**  Brick materials | Ceramic bricks  Clay bricks  Clay matrix bricks  Fired clay bricks  Agro bricks  Earth bricks  Light fired clay bricks  Lightweight bricks  Thermally efficient burnt clay bricks  Eco-friendly clay bricks  Eco-friendly porous ceramic bricks  Unfired earth blocks/ bricks  White brick fuel cell  Building block for masonry wall | [6, 15, 77, 78, 80, 86, 97, 101–105, 26, 31, 38, 43, 55, 57, 59, 64] |
| **Category 3**  Materials/biocomposites for structural and/or reinforcement applications | Natural fiber/polymer composites (NFPCs)  Polymer matrices for lightweight structural applications  Reinforced polypropylene composites  (wall panel)  Bio-epoxy resin reinforced green composites  Bio-based polymers  Wallpaper  Hybrid polypropylene composites  False ceiling tiles  Fiber-cement  Concrete walls  Cement-bonded particleboard  Binderless fibre-board  Reinforced polypropylene  Reinforced composites  Particleboard  Fibreboards  Unitary (or ‘‘monolithic”) structural components and assemblies  Earth Plaster Composites  Panels, door shutters, door frames, roofing sheets and dough molding compounds  Roofing tiles, ceiling plates, thin sheets, wall panels  Lightweight building components  Structural sheathing materials  Composite boards/panels | [30, 43, 106–113, 57, 58, 61, 79, 83, 96, 99, 100] |
| **Category 4**  Materials for thermal and/or acoustic insulation in buildings | Joints between walls, windows, floor, and roof  Recycled waste panels  Insulation panels  Bio-based insulations  Structural materials for low-energy buildings  Thermal insulating plate  Reinforced panels  Particleboards  Bio-Based Plastics | [14, 31–33, 62, 66, 98, 110, 114] |
| **Category 5**  Road construction materials | Sustainable bio-modified asphalt  Asphaltic concrete  Modified Asphalt Binders | [81, 95, 115, 116] |

**Table 2.** Main properties and parameters of the bio-based products

|  |  |  |
| --- | --- | --- |
| **Properties** | **Parameter** | **References** |
| **Physical** | Sorptivity  Bulk density  Microstructure  Specific Gravity  Drying shrinkage  Apparent Porosity  Water absorption | [6, 7, 55, 58, 61, 64, 65, 77, 78, 80, 81, 88, 14, 89, 91, 92, 95, 97, 98, 100, 102, 104, 105, 15, 106–110, 112, 114–116, 22, 25, 28, 32, 35, 53] |
| **Mechanical** | Durability  Workability  Flowability  Flexural strength  Tensile strength  Impact strength  Young’s modulus  Thickness swelling  Compressive strength | [6, 7, 32, 35, 36, 38, 53, 57, 58, 61–63, 14, 64, 68, 70–75, 82, 88, 15, 89, 91–94, 96, 97, 99, 100, 102, 18, 103–109, 111, 113, 114, 22, 116, 26–28, 31] |
| **Chemical** | Loss on ignition  Chloride resistance  Resistance to chloride  Acid and sulphate resistance  Heavy metals content/leaching toxicity | [7, 18, 22, 25, 28, 53, 55, 64, 78, 98] |
| **Others** | Mineralogical analysis  Sound absorption  Thermal conductivity  High temperature resistance  Thermogravimetric analysis | [6, 7, 59, 62, 64, 68, 73, 77, 78, 92, 98, 99, 14, 100, 102–107, 109–111, 26, 114, 31–33, 38, 55, 57] |

**Table 3.** Main types and properties of AWBs used by category

| **Type of biomaterials** | **Main type and form of AWB** | **Main characteristics of the by-product** | **Effects on the properties of bio-based products** | **References** |
| --- | --- | --- | --- | --- |
| **Category 1**  Binding materials, aggregates and/or additives for soil, cement and/or concrete | Rice Husk (Ash)  Sugarcane bagasse (Ash)  Coconut husks (Ash) | Rich in amorphous silica  High pozzolanic activity  Pore-forming additives  Lower specific gravity  Increases setting time  lower thermal conductivity | Improved mechanical properties (Compressive, flexural, shear and tensile strength)  Reduction of thermal conductivity  Density reduction (lighter materials)  Better resistance to acid attack  Increased resistance to chloride penetration  Lower water absorption  Reduced permeability  Improved durability  Improved workability  Improvement of the geotechnical properties of the soil | [6, 7, 35, 38, 52, 53, 56, 60, 63, 67–69, 15, 70–72, 74, 75, 82, 90, 92, 113, 18, 22–24, 28, 31, 34] |
| **Category 2**  Brick materials | Rice Husk (Ash)  Cereal Straw (Ash –fibers)  Sugarcane bagasse (Ash) | Increased ceramic strength  Increase in amount and size of pores  Reduction of bulk density  Reduction of brick weight  Reduction of the thermal conductivity coefficient  Lower dead load  Improved thermal insulation properties  Improved static properties  Reduced plasticity | [15, 26, 104, 105, 31, 55, 59, 64, 77, 78, 80, 102] |
| **Category 3**  Materials/biocomposites for structural and/or reinforcement applications | Cereal Straw (Fibers)  Rice Husk (Ash)  Coconut husks (Fibers - Ash) | Lower specific gravity  High percentage of fibers  Longer fibers  Tubular internal structure, strong and efficient  Low density  High cellulose and hemicellulose content | Improvement of impact, tensile and flexural strength  Better resistance to water and thickness swelling  Low weight  Good sound absorption  Improved load transfer and crack arrest efficiency  Improved thermal insulation/ thermal stability  Better structural integrity and energy dissipation  Good stiffness for civil infrastructural applications  Control of shrinkagecracks  Decreases erosion of materials  Improveds shrinkage properties  Better absorption of impact energy | [15, 30, 108–112, 114, 57, 58, 61, 83, 96, 99, 100, 106] |
| **Category 4**  Materials for thermal and/or acoustic insulation in buildings | Rice Husk (fibers)  Cereal Straw (fibers)  Sugarcane bagasse (fibers) | Better thermal and environmental performance  Good thermal conductivity and resistivity  Satisfactory results in mechanical and thermophysical performance  High sound absorption coefficients  Lower density | [14, 31–33, 66, 98, 114] |
| **Category 5**  Road construction materials | Rice Husk (Ash-fibers)  Coconut Shell  (Small aggregate)  Sugarcane bagasse (Fibers)  Palm shells  (coarse aggregate) | Increased resistance to thermal cracking of the pavement at low temperatures  Reduced permanent (plastic) deformation at high road surface temperatures under traffic loads  Improvement of -the rutting factor  Improved fatigue resistance of the asphalt binder  Good range stability Marshall  Improved mechanical properties | [81, 115, 116] |

**Table 4.** Limitations and improvement alternatives for bio-based products

|  |  |  |
| --- | --- | --- |
| **Limitations and/or disadvantages** | **Alternatives to reduce adverse effects** | **Reference** |
| Increase LOI  Reduction of workability  Lower strength activity index (SAI)  Higher drying shrinkage  High water absorption  Susceptibility towards chemical attack  Effect of moisture content on internal bonding  Dimensional stability  Lower durability  Crack formation | Additional treatments  Chemical and/or heat treatment of fibres  Pre-treatment methods (screening, burning, drying, firing)  Incorporation of nanomaterials nano silica, nano alumina  Inclusion of bacteria in rice husk  Addition of stone dust | [15, 18, 54, 58, 62, 91, 106, 107, 110–112, 114, 21, 22, 25, 29, 31, 32, 34, 35] |

**Table 5**. Main benefits by dimension

| **Dimension** | **Description of main benefits or advantages** | **References** |
| --- | --- | --- |
| Economic | New value chains  New market opportunities  Savings raw materials  Reduction of material production costs Reduction of waste landfill fees  Reduction of transportation costs  Reduction in construction cost  Reduction of road construction and maintenance in rural areas costs | [7, 15, 55, 58, 60, 64, 67, 70, 74, 82, 85, 86, 23, 91, 96, 97, 99–101, 105, 107, 115, 26, 28, 29, 31, 32, 37, 42] |
| Environmental | Carbon dioxide (CO2) emissions reduction  Reducing global warming and climate change  Increasing energy efficiency  Reduction in consumption of thermal and electrical energy  Landfill reduction  Improving the management of the AWB  Recycling and valorisation of AWB  Values of leaching toxicity much lower  Reduced consumption of natural clay reserves  Reducing the exploitation of natural resources  Reduction of AWB burning  Reduction of water consumption  Reduced consumption of virgin raw materials  Reduction of soil erosion | [6, 7, 32–38, 42, 52, 54, 14, 55–58, 63, 64, 66–69, 15, 70, 72–78, 82, 83, 23, 85–87, 91, 94, 97–101, 24, 103, 105, 106, 108, 111, 114, 115, 26, 28, 29, 31] |
| Social | Creation of new jobs  Enhancing the economic power of local communities.  Low-cost building and/or infrastructure development in low-income regions  Use of locally available materials for infrastructure works in developing countries  Reduce social housing cost  Functional, high quality, comfortable and affordable environments for building occupants  Societal welfare  Healthy indoor environment  Population health benefits | [14, 31–33, 87, 91, 93, 100, 105, 115] |

**Table 6.** European Union projects

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Proyect name** | **Objetive** | **Type of AWB** | **Type of bio-based prodcuts** | **Project implementation date** | **R** |
| Grant agreement ID: CR147691-BRE21154 | Development of new construction materials based on mineral binders derived from waste | Straw and husk | Mineral binder | May-July 1994 | [117] |
| ECO-PCCM | To introduce a new class of eco-friendly and cost-effective polymer composite construction material | Rice straw, hemp, kenaf, cotton, sisal, flax | Renewable eco-friendly composites for structural components | October 2004 -  September 2007 | [118] |
| SYNPOL- Biopolymers from Syngas Fermentation | Establish a platform for integrating synthesis gas production and fermentation technologies for cost-effective commercial production of high value-added biopolymers. | Straw | Biopolymers | October 2012 -  September 2016 | [119] |
| REHAP | Development of new materials for the construction sector from agricultural and forestry residues | Wheat straw | Thermoplastic PU Adhesive  Wooden boards  Cement | October 2016 -  March 2021 | [123] |
| AgroCycle | To convert low-value agricultural waste into highly valuable products, achieving a 10% increase in waste recycling and valorisation by 2020. | Horticultural waste | High value-added biopolymers | June 2016 -  May 2019 | [128] |
| Mycotaff | A renewable bio-based material that enables efficient, cost-effective production of high-quality insulation, packaging, dry-wall, and other building materials | Mushroom mycelia | Prefabrication walls  material for insulation and other building applications | June -  september 2018 | [129] |
| BARBARA | The development of novel bio-based engineering bioplastic materials to be validated as functional prototypes with advanced properties for the building and automotive sectors. | Lemon, carrot, pomegranate and almond shell | Polyester-Based Biocomposites  Moulds for Resin Transfer Moulding and truss joint prototypes | May 2017-  October 2020 | [130] |
| B-SMART | To develop new intelligent cementitious nanocomposites for multifunctional built infrastructure made by combining ordinary Portland cement (OPC) with cheap bio-nanomaterials synthesised from root vegetable waste such as carrot and beetroot waste streams produced by the food processing industry. | Carrot and beetroot waste | Intelligent cementitious nanocomposites for multifunctional built infrastructure | September 2018 - September 2020 | [131] |
| NoAW : No Agro-Waste | To generate innovative efficient approaches to convert growing agricultural waste issues into eco-efficient bio-based products opportunities with direct benefits for both environment, economy and EU consumer. | Maize silage  grape stalks  Vine shoots /wine pomace  Fruit and vegetable wastes | Biocomposites/Biodegradable polymers - polyhydroxyalkanoates (PHAs). | October 2016 -  January 2021 | [124] |

R: Reference