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REVIEW

Hygroscopy and adaptive architectural façades: an overview

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Abstract
Hygroscopic properties of wood have been utilized in adaptive façades to respond to variation in humidity levels. Shape-shifting materials have been developed to replace mechanical actuators that respond to climatic variation with zero-energy consumption. This paper presents a systematic review of the literature on the use of hygromorphic behaviour in developing adaptive architectural façades, with the primary focus of identifying the venues of implementation of hygroscopic actuation in adaptive facades. The paper triangulates the intersection between hygroscopic design parameters with manufacturing strategies and their application as a passive motion mechanism in adaptive facades. This review focuses on state-of-the-art experimental work in hygroscopic design, with specific interest in manufacturing methods of hygromorphic adaptive façades, response motion behaviour evaluation and tracking, analysis of the current applications of hygromorphic design in real weather conditions, and performance prediction. Results reveal that most of the studied papers focus on the response behaviour of programmable materials to variation in moisture content and the implementation of hygroscopic design in adaptive façades. From the literature analysis, it was shown that programming the response behaviour of hygroscopic materials mainly takes place through variation in fabrication methods, followed by passive layer configurations, which act as actuators that are controlled by differences in layer properties.

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Introduction

Programmable materials are known as smart materials with the ability to program their mechanical properties during the fabrication phase of the material in a reversible motion in response to external stimuli (Vazquez et al. 2019). Addressing a wide range of sustainability considerations, hygroscopic properties of wood have been studied as a passive natural response mechanism that responds to fluctuation in humidity levels with zero-energy consumption (Holstov et al. 2015b).

Fox and Kemp suggest the "end of mechanism paradigm" to derive motion using passive and soft systems to replace typical mechanical actuators (Fox 2016). The use of passive biological techniques has been extended in the context of interactive and responsive architecture (Fox 2016). Latent properties of smart materials have also been utilized to encode passive motion response (Kretzer 2017). These passive motion approaches have been associated with low-cost and low-tech systems in responsive and adaptive architectural skins.

This paper presents a systematic mapping of the literature, following the "systematic quantitative approach" method by Pickering and Byrne (2014). It introduces the main discourse of hygroscopic design, salient gaps in the literature, and potential themes for future research. The material presented includes both quantitative and qualitative analyses. Quantitative analysis is used in surveying and calculating the contribution weight of studies that address the use of hygromorphic materials in adaptive systems, while qualitative analysis is used to identify from the literature aspects of hygromorphic design programmability, performance evaluation, and fabrication methods to enhance the efficiency of programmable hygromorphic design.

In order to systematically map the primary literature for this paper, the main keywords and topics were identified through the relevant research databases. The keywords used in searching the databases were restricted to hygroscopic properties of wood in adaptive façades and included "Hygroscopic facades", "Hygro facades" and "Hygromorphic skin". This was conducted primarily using Google Scholar which includes several research databases such as Scopus, Elsevier, Taylor and Francis. The review included scientific papers and articles published between 2010 and the current date of writing this paper in 2023. From a total of 3194 papers that were relevant to hygroscopy in general, manual filtration was applied to identify relevant papers and to remove duplicate papers. Based on this filtration, we included 41 papers that focus on utilizing hygroscopic properties of wood as a design element on different levels that are relevant to adoption in adaptive architectural façade design. The literature was reviewed and analysed to reveal the research contribution towards each parameter.

We identified the state of the art of hygromorphic wood in façade design to fall under three categories: (1) encoding hygroscopic behaviour of wood in experimental phases, (2) computational approaches of modelling and tracking hygroscopic behaviour, (3) and implementation of hygroscopic behaviour as a passive responsive motion mechanism. The studies included in this review were peer-reviewed publications. We focused on studies that encompass the development of architectural façades and shading systems, and excluded studies that involve materials science research. We included only studies with design elements and configurations that are derived from the hygroscopic properties of wood. Due to the small number of full-scale implementations of hygroscopic design, we also included early-stage prototypes and studies that demonstrate solutions for specific parts of the building envelope.

The paper aims to present the state of the art in utilizing hygroscopic design as a passive actuation mechanism that responds to variation in humidity with zero-energy consumption. We are also interested in showing the significance and contribution of multidisciplinary research that leads to enhancing and developing new composite materials based on merging base hygroscopic wood layers with other materials. The research therefore targets the following questions:

a. Which hygroscopic design parameters and manufacturing strategies have been utilized to enhance architectural adaptive facades?
b. How is the motion of hygroscopic materials tracked and evaluated?
c. How is hygroscopic design implemented in adaptive facades?

In the next section, we report on concepts, approaches, and solutions identified in the 39 papers under study that address the aforementioned questions. Then, literature is studied through three main aspect: (1) Parameters and manufacturing strategies utilized with the purpose of enhancing architectural adaptive façades, including direction of wood cut, type of wood, grain orientation, passive layers, thickness, dimensional ratio, geometrical configuration, perforations, and moisture content, in addition to fabrication methods. (2) Methods of tracking and evaluating the motion of hygroscopic materials. (3) Implementation of hygroscopic design in adaptive façades.

Hygroscopy and architecture

A significant amount of electrical energy is consumed in mechanical actuators of typical architectural adaptive systems in order to transform electrical energy into mechanical motion. Passive actuation mechanisms that are stimulated by variation in weather conditions however, as found in the natural response of plants to external stimuli, allow for a significant reduction in the energy consumption of mechanical actuators (Poppinga et al. 2017).

With the increased awareness of energy conservation, there is a shift towards using wood as a construction material due to its low carbon impact and embodied energy in comparison to steel, aluminium, and concrete. Carbon is stored in wood and is released when trees die, or wood is burnt or deteriorated, while it remains stored in utilized wooden products or paper (Forest Products Laboratory 2010). One of the primary properties of wood that are related to adaptive systems in architecture is anisotropy. Anisotropy is considered the main factor that affects the control of shape change to achieve designed motion.

Hygroscopic behaviour in plants is noted as a passive motion response with zero-energy consumption. It is mainly known as the adaptation behaviour of plants to their environment that relies on structural arrangements and layer configurations. This phenomenon can be found in several plants such as the response behaviour of pinecones to variation in humidity. The effect of humidity and water content in plants affects their form and behaviour (Zhan et al. 2023). Moreover, hygroscopic motion in plants is widely used as a method for seed dispersal (Elbaum and Abraham 2014). The conifer cone is one of the well-known hygroscopic structural plants that opens when wet and closes when dry. This reversible passive motion mechanism is due to the bilayer structure of the plant, as it has a passive and active layer that varies in the ability to absorb water causing this motion mechanism (Zhan et al. 2023). This is the main principle of hygroscopic design which relies on the variation of the expansion coefficient of the layers, thus initiating a passive motion mechanism. Vascular plants that include conifers and flowering plants handle water in either a standard liquid state or bound water in cells (Cocusse et al. 2022). The humidity or water-actuated motion in plants can be found in several types such as bending motion in pinecones, spiral curling motion in spikemoss, and Helix seed pod. However, the hygroscopic motion response speed varies across plants; some are triggered within seconds (seed pod) while others are triggered within hours (pinecone and spikemoss). Hygro-deformation can even be found in dead plants when losing water causes the plant to crack and warp in different directions. Researchers are taking this hygroscopic passive motion response to a wider scale to design zero-energy consumption motion mechanisms (Zhan et al. 2023). This demonstrates the need for a multidisciplinary study area to study shape-shifting materials as a climatic responsive zero-energy motion mechanism that mimics the response behaviour of plants.

Shape-changing or shape-shifting materials have allowed for new solutions in several disciplines such as medical devices that unfold inside the human body, passive robotic actuators, and architectural elements that are responsive to specific environmental conditions (Oliver et al. 2016). Recently, the implementation of hygroscopic materials, particularly wood, has been utilized for low-tech smart materials and passive responsive systems. Wood is characterized by its hygroscopic properties that allow it to absorb water in its dry condition until it reaches equilibrium (Menges 2015). However, researchers in the area of adaptive systems have been "programming" the hygroscopic properties of wood to be triggered by multiple stimuli other than just variation in moisture content, such as variation in temperature, as shown in Table 1.

Two main categories of wood actuation can be identified from the literature: (1) actuation by moisture and (2) actuation by temperature variation. Moisture content in natural wood samples and 3D printed wood has been studied primarily through three activation mechanisms: (a) controlling relative humidity in a climate-controlled chamber, (b) water submersion, and (c) water spraying. Some papers have used more than one activation mechanism to compare between their effect on wood behaviour. For example, Holstov et al. (2015b) studied the effect of two activation mechanisms such as water spraying and controlled relative humidity on wood motion response. Correa et al. (2015) tested three activation mechanisms including water submersion, relative humidity in a climate-controlled

Table 1 Classification of studies based on type of wood actuation

Wood actuation stimulus	References
1. Moisture content	a. Relative humidity Rüggeberg and Burgert (2015), Holstov et al. (2015a), Dierichs and Menges (2016), Vailati et al. (2017, 2018a, b), Arends et al. (2017), Grönquist et al. (2018), Abdelmohsen et al. (2018, 2019a, b, c), Wood et al. (2018), El-Dabaa and Abdelmohsen (2018), Anis (2019), Augustin and Correa (2019), Pelliccia et al. (2020), Vazquez and Gursoy (2020), Giachini et al. (2020), Grönquist et al. (2020), Nan et al. (2020), Tomec et al. (2021), Cheng et al. (2021), Ibrahim et al. (2022a) b. Water submersion Le Duigou and Castro (2017), Le Duigou et al. (2021), Tahouni et al. (2021) c. Spraying Holstov et al. (2017), El-Dabaa et al. (2021b), El-Dabaa and Salem (2021) d. Relative humidity and spraying Holstov et al. (2015b), Dierichs et al. (2017)
2. Temperature	El-Dabaa et al. (2020), El-Dabaa and Abdelmohsen (2022a, b)
3. Temperature and moisture content	a. Relative humidity and temperature Reichert et al. (2015), El-Dabaa and Abdelmohsen (2019), Aly et al. (2021), Ibrahim et al. (2022b) b. Relative humidity, water submersion and temperature Correa et al. (2015) c. Relative humidity, spraying and temperature Ibrahim et al. (2020)

chamber, and heat radiation along with moisture intake. The submersion in water and water spraying activation mechanisms have been studied as an experimental approach in the studied literature. However, as an adaptive façade, the literature still does not capture for example rain-activated full-cycle façade studies.

As shown in Table 1, researchers have been studying the effect of several stimuli on wood motion response, with different weights in terms of contribution and focus. The focus in the literature has shown that using moisture content only as a stimulus to activate wood motion response is the most studied stimuli, followed by variation in both moisture content and temperature, and then the variation in temperature only. This goes in parallel with the properties of wood that is mainly stimulated by moisture content; however, the actuation of wood by temperature requires wood lamination with other metals such as aluminium or copper. An example is the laminated composite of hygromorphic thermo-bimetals (H_MT_M) that can be actuated by variation in temperature or humidity (El-Dabaa and Abdelmohsen 2019). Furthermore, the temperature of water used in spraying on wood affects its motion response, as the angle of curvature and speed response of wood when actuated by hot water is more than by tepid water (Ibrahim et al. 2020).

Encoding hygroscopic design parameters as a shape-shifting mechanism

The process of encoding and controlling the hygroscopic motion response of wood when exposed to difference in humidity levels involves several aspects. According to the bilayer structure of hygroscopic-based composites, the expansion of layers varies when exposed to variation in humidity levels, thus causing a passive bending motion (Arends et al. 2017; Holstov et al. 2015b). Hygroscopic deformation leads to deformation of wood, the development of internal stresses, or both. Taking this into consideration can optimize other hygroscopic design parameters such as thickness. The hygroscopic properties of wood are studied as a method to achieve double-curved wooden surfaces, in addition to its significance in terms of upscaling, as with the self-shaping wooden Urbach tower (Bechert et al. 2021). Programming and controlling wood response to humidity takes place during the lamination process of wooden samples. Two sets of properties were identified as governing this programmability: (a) embedded properties of wood (Abdelmohsen et al. 2019a, b), and (b) design-controlled properties of wood (El-Dabaa and Abdelmohsen 2022a). Programming the hygroscopic motion response is meant to control shape change according to hygroscopic design parameters.

The effect of embedded properties of wood on its passive motion response has been thoroughly investigated in several studies, such as grain orientation, thickness ratio of layers and stiffness, and types of wood (Holstov et al. 2015b). Table 2 shows an overview of the studies that have attempted to test the effect of each parameter on wood morphology when exposed to variation in humidity, including both embedded parameters, such as grain orientation, dimensional ratio, and wood type; and design-controlled parameters that take place during the lamination process, such as the percentage, direction and location of passive laminated layers (El-Dabaa et al. 2020, 2021b). Based on this classification, most of the papers under study were shown to focus on fabrication methods as the main hygroscopic design parameter, including both lamination and 3D printing, followed by the use of design variation of passive layers, then grain orientation and dimensional ratio. This contribution weight in the literature shows that the fabrication process can be seen as the main driver for hygroscopic wood actuation, as it depends on the difference in the layer properties of the sample. However, the fabrication process mainly requires merging two or more hygroscopic design parameters, such as the passive layer design configuration and grain orientation.

Moisture content

Wood is characterized by its hygroscopic properties that can absorb and handle water from its surroundings (Cave 1978). Moisture content in wood denotes the ratio between the weight of water and wood in its dry state (Abdelmohsen et al. 2019a). Programming the initial state of wood relies on its moisture content in the initial state. Figure 1 shows an example of a programmed initial state for a single layer beech veneer sample with a 0° tangential cut. The sample is encoded by folding it in a wet condition and leaving it to completely dry; this is set as a pre-programmed

Table 2 Classification of studies based on encoding hygroscopic design parameters in architectural adaptive facades

Encoding hygroscopic design parameters	References
Embedded parameters	Direction of wood cut Holstov et al. (2015b), Reichert et al. (2015), Wood et al. (2018), Vailati et al. (2018b), Ibrahim et al. (2022b)
	Type of wood Reichert et al. (2015), Abdelmohsen et al. (2019a), Augustin and Correa (2019), Ibrahim et al. (2022b)
	Grain orientation Reichert et al. (2015), Holstov et al. (2015b), Wood et al. (2018), Abdelmohsen et al. (2019a, b, c), El-Dabaa and Abdelmohsen (2019), Anis (2019), Pelliccia et al. (2020), El-Dabaa et al. (2020), Nan et al. (2020), Ibrahim et al. (2022b)
	Thickness Holstov et al. (2015b), Rüggeberg and Burgert (2015), Vailati et al. (2017, 2018b), Wood et al. (2018), Grönquist et al. (2018), El-Dabaa and Abdelmohsen (2019), Pelliccia et al. (2020), El-Dabaa et al. (2020), Ibrahim et al. (2022b)
	Dimensional ratio Reichert et al. (2015), Vailati et al. (2017, 2018a, b), Wood et al. (2018), Grönquist et al. (2018), Anis (2019), Abdelmohsen et al. (2019b), Grönquist et al. (2020), El-Dabaa et al. (2020), Nan et al. (2020), Ibrahim et al. (2022b)
	Moisture content Holstov et al. (2015b), Reichert et al. (2015), Abdelmohsen et al. (2019a, b), Nan et al. (2020)
Design-controlled parameters	Passive layers Type of passive layer: Reichert et al. (2015), Rüggeberg and Burgert (2015), Holstov et al. (2015b, 2017), Wood et al. (2018), Abdelmohsen et al. (2019a, b, c), Augustin and Correa (2019), El-Dabaa and Abdelmohsen (2019), Pelliccia et al. (2020), El-Dabaa et al. (2020), Aly et al. (2021), Ibrahim et al. (2020, 2022a) Location of passive layer: Holstov et al. (2015b), Vailati et al. (2018b), El-Dabaa et al. (2020, 2021b)
	Geometrical configuration Reichert et al. (2015), Wood et al. (2018), Abdelmohsen et al. (2019b), Anis (2019), Grönquist et al. (2020), Nan et al. (2020), Ibrahim et al. (2022b)
	Perforations Anis (2019), Cheng et al. (2021), Vailati et al. (2017), Ibrahim et al. (2022b)
	Fabrication methods Correa et al. (2015), Reichert et al. (2015), Rüggeberg and Burgert (2015), Holstov et al. (2015b, 2017), Dierichs and Menges (2016), Vailati et al. (2017, 2018a, b), Wood et al. (2018), Abdelmohsen et al. (2018, 2019a, b, c), Augustin and Correa (2019), El-Dabaa and Abdelmohsen (2019), Pelliccia et al. (2020), Grönquist et al. (2020), El-Dabaa et al. (2020, 2021b), Nan et al. (2020), Vazquez and Gursoy (2020), El-Dabaa and Salem (2021), Cheng et al. (2021), Aly et al. (2021), Tahouni et al. (2021), Ibrahim et al. (2022a, 2022b)

initial state. The motion response is a reversible process that returns back to its initial state when it dries. When exposed to an increase in humidity levels, the sample transforms to a flat state then returns back to the pre-programmed folded form upon drying. Encoding motion generally takes place under either a wet or dry lamination process to control the initial state of the sample. The lamination state condition (flat or curved state) encodes the initial state of the hygromorphic composite material.

Type of wood

Wood is generally divided into hardwoods and softwoods that differ primarily in their fibre microstructures. Hardwoods are porous with open ended stacked vessels, resulting in continuous tubes that facilitate water movement. Softwoods on the other hand are cone-bearing plants with no pores or vessels. They are rather formed by needles or scale-like evergreen leaves. In hygroscopic design, beech and ash for example are considered hardwoods, while fir and spruce are considered softwoods (Forest Products Laboratory 2010). These types vary in their ability to absorb and handle water according to their shrinkage values (Schroeder 1972). The percentage of shrinkage values varies according to the type of wood (Reichert et al. 2015). For example, within a tangential cut, American beech (hardwood) has a shrinkage value of 11.9%, while fir (softwood) has a shrinkage value of 7.4% (Forest Products Laboratory 2010), with a differential shrinkage value of 4.5%.

Based on this difference between hardwoods and softwoods, hardwood is used to initiate motion due to its higher expansion value, while softwood is usually used as a passive layer to regulate motion (Abdelmohsen et al. 2019a; Rüggeberg and Burgert 2015). However, the selection of which layer can initiate the motion can be changed according to the type of motion response and speed needed. Wooden samples with abnormalities such as knots and bird's eyes need to be excluded from use in hygromorphic composites to achieve a regular motion response (Holstov et al. 2015b). Augustin and Correa (2019) studied the difference in motion response for different species of hardwood such as black cherry, hard maple, black walnut, and European beech, and the results show that European beech with straight grain orientation tends to have the highest deformation. It was also demonstrated by Abdelmohsen et al. (2019a) that hardwoods tend to have a faster response and a higher deflection value than softwoods.

Fig. 1 Programming the initial state of beech veneer using its moisture content, **a** initial state of fully immersed wood, **b** time lapse showing its response through a duration of 3 min

Direction of wood cut

Wood, as an orthotropic material, is known by differences in its mechanical properties and shrinkage values according to the direction of three main timber cuts: longitudinal (parallel to the wood fibres), tangential (tangent to the annual rings) and radial (from the centre pith to bark) (Forest Products Laboratory 2010; Holstov et al. 2015b; Abdelmohsen et al. 2019a).

Typically, tangential cut orientation achieves maximum responsiveness, followed by the radial then the longitudinal cut orientation (Reichert et al. 2015). Acquiring a maximum angle of deflection in bilayer hygromorphic composites can be achieved by having an active layer with a tangential cut using a rotary or plain cut, and a passive layer with a radial, longitudinal or non-hygroscopic layer. Rotary cut veneer has the highest hygro-expansion due to its exact alignment with the growth grain (Holstov et al. 2015b). However, in the upscaling process, cross-lamination and joint design have been studied to achieve high deflection value with less structure weight (Grönquist et al. 2020).

Grain orientation

Grain orientation defines the main direction of wood fibres through the main axis of a given wooden sample. It plays a significant role in controlling the type and direction of motion and response speed in hygromorphic composite materials (Reichert et al. 2015; Abdelmohsen et al. 2019c). The angle lies between the grain and the short axis of the sample; for example in a rectangular shaped veneer sample, 0° fibres are parallel to the short axis, 90° fibres are parallel to the long axis, while 45° fibres represent the diagonal of the sample (Abdelmohsen et al. 2019a).

Several experiments conducted on wood veneer revealed that the direction of grain orientation directly affects the response behaviour of wooden samples in terms of both angle of curvature and response speed. Samples with 0° grain orientation tend to have the fastest response speed associated with the highest curvature, followed by samples with diagonal grain orientation and then samples with 90° grain orientation. In terms of surface curvature, samples with 0° and 90° grain orientation were generally shown to exhibit a single curved surface, while samples with a 45° diagonal grain orientation were shown to exhibit a twisted motion response (Abdelmohsen et al. 2019c). Maximum curvature change was shown to take place in the direction orthogonal to the active layer's grain orientation (Reichert et al. 2015).

Passive layers

Passive layers magnify the effect of active layers by providing a constraint to the hygro-expansion process, therefore driving the composite as a whole to bend (Holstov et al. 2015b). Several studies have investigated multiple types of passive layers to control either a specific angle of curvature, response speed or stimulus, as shown in Table 3. Based on the classification in the table, it seems that several types of wood are usually studied as the passive one more than other materials.

Table 3 Classification of studies that involve lamination with different types of passive layers in architectural adaptive façades

Types of passive layer	References
Wood	Holstov et al. (2015b), Rüggeberg and Burgert (2015), Reichert et al. (2015), Dierichs and Menges (2016), Dierichs et al. (2017), Vailati et al. (2017, 2018a, 2018b), Abdelmohsen et al. (2018, 2019a, b, c), Wood et al. (2018), Ibrahim et al. (2020, 2022b), Pelliccia et al. (2020), Grönquist et al. (2020), Nan et al. (2020)
Metals	El-Dabaa and Abdelmohsen (2019), El-Dabaa et al. (2020)
Silica gel and potassium chloride	Aly et al. (2021), Ibrahim et al. (2022a)
Nylon	Augustin and Correa (2019)
Glue moisture isolation	El-Dabaa et al. (2021b)
Wood, jute fabric and fibre glass	Holstov et al. (2017)

In hygroscopic design, wood is used primarily as the main active layer that initiates motion, while passive layers were shown to include either softwoods or other types of materials, such as nylon, rubber, metals, fibre glass, etc. Laminated wooden samples use hardwood as the active layer, and softwood as the passive layer that restrains sample dimensional change, resulting in a curved surface and reducing the overall response directionality and speed, in addition to developing internal stress loads that tend to control the motion response. This motion behaviour can be reduced however depending on several aspects, such as passive wood with a small expansion coefficient, the type of wood cut, and passive wood layers that are smaller in thickness than active layers. Materials with low hygroscopicity on the other hand, such as synthetic polymers, jute fabric and fibre glass reinforced composites, were shown to be used as a passive layer to maintain the stability of dimensional change (Holstov et al. 2015b, 2017).

Thickness

The lamination of passive and active layers to achieve both maximum deflection values and structural efficiency requires optimizing the thickness and stiffness value for each layer. Several experiments have validated that samples with small thicknesses have a higher response speed and larger deflection angle due to their ability to absorb moisture at faster rates than thicker samples (Rüggeberg and Burgert 2015; Wood et al. 2018; Vailati et al. 2018b; Grönquist et al. 2018; El-Dabaa and Abdelmohsen 2019; Pelliccia et al. 2020; El-Dabaa et al. 2020). Thick samples are shown to be more durable than thin samples, but tend to have slower responses to variation in humidity. The optimal thickness ratio differs according to the specific lamination configuration which involves the type of each layer and grain orientation (Holstov et al. 2015b). Milling has also been studied as a strategy for enhancing the response behaviour and speed for thick samples in active layers, where the milling direction acts as a grain orientation direction that encodes the motion direction of the sample (Vailati et al. 2017).

Dimensional ratio

Dimensional ratio implies the length-to-width ratio for a given wooden sample. Several experiments have been conducted to show the effect of dimensional ratio on the behaviour of wooden samples (Vailati et al. 2017, 2018a, b; Wood et al. 2018; Grönquist et al. 2018, 2020; Anis 2019; El-Dabaa et al. 2020; Nan et al. 2020). The type of behaviour response was shown to vary according to dimensional ratio. When stimulated by increase in moisture content, wooden samples were shown to exhibit different types of responses, including acting as a beam, plate or shell. Samples with lengths larger than their widths and thicknesses were shown to act as beam structures with single dimensional curvature and negligible deformation along the width direction. Samples with widths larger than their lengths and thicknesses were shown to act as plates when programmed as flat in their initial state. Samples with the same proportions were shown to act as shells when programmed as curved in their initial state (Abdelmohsen et al. 2019b). In terms of response speed and deflection, most experiments demonstrate that narrow samples tend to respond more than wider samples (Reichert et al. 2015). Abdelmohsen et al. (2019b) and Wood et al. (2018) also show that samples with higher length-to-width ratios (narrow samples) exhibit a higher response speed and larger angle of curvature. Understanding the effect of dimensional ratio on the response behaviour of hygromorphic design allows for encoding its passive motion response in the fabrication phase of the material when exposed to variation in humidity levels (Wood et al. 2018; Abdelmohsen et al. 2019b).

Geometrical configuration

This section highlights studies that explore the effect of geometrical configuration of hygroscopic prototypes on motion response behaviour when exposed to variation in external stimulus. A comparison between the angle of curvature in triangular and rectangular samples showed that triangular samples have higher curvature than rectangular ones (Anis 2019). This is because expansion occurs from the base to the vertex in triangular samples which in turn have less material thus less deformation resistance (Anis 2019). The “Hygroscapes” workshop conducted at the American University in Cairo fabricated several adaptive façade prototypes with triangular and rectangular wooden samples with different aspect ratios (Abdelmohsen et al. 2019b). The relation between the size, geometry and thickness of a given sample has been studied, demonstrating that thicker samples tend to take more time to balance the moisture level of the samples with the surroundings (Reichert et al. 2015). Wood et al. (2018) studied the proportions of geometrical configurations of rectangular and square samples, showing that longer samples have higher speed response and less angle of curvature. Another comparison between wooden geometrical configurations, including squares, hexagons, and bowtie samples cut from squares was also studied (Nan et al. 2020). Results show that irregular wooden geometries have larger angles of curvature than square ones. This is due to the fact that decreasing the passive layer area reduces the resistance of the bending force (Nan et al. 2020).

Perforations

Large-scale perforated self-shaping structures have been tested using a hybrid additive fabrication approach, through merging the responsive behaviour of hygroscopic laminated wood with 3D printing. A few papers have attempted to study perforations, although this programs material properties and response, in addition to tailoring the 3D printed meta-structures and hygroscopic wood actuators (HWAs) with robotic fabrication, thus controlling stiffness without increasing weight (Cheng et al. 2021). Anis (2019) shows that a perforated bamboo veneer sample laminated with film tends to deform less than a solid sample due to the division of the grains. Moreover, adding milling grooves in a wooden thick sample helps increase the angle of deflection and response speed (Vailati et al. 2017).

Fabrication methods

The main essence of hygromorphic design relies on having two laminated layers that vary in their expansion coefficient, leading to dimensional transformation when exposed to variation in humidity and consequently passive motion response (Holstov et al. 2015b; Abdelmohsen et al. 2019a). Several methods have been used in the lamination of active and passive layers such as gluing, mechanical fixation, spot gluing and direct lamination (Holstov et al. 2017). Standard gluing and direct lamination methods are shown to prevent the permeability of water and moisture in between the layers, therefore slowing the response rate. Spot gluing has the overall highest response speed and is quicker to dry than mechanical fixing (Holstov et al. 2017). Other controlled hygroscopic parameters have also been studied such as the fixation position of a given wooden sample, and the isolation of specific parts of the sample with several locations and percentages (El-Dabaa et al. 2021b).

Table 4 presents an overview of the different fabrication methods for hygromorphic adaptive façades, including those that utilize natural wood as well as 3D printed wood, while maintaining the same concept of laminated wooden actuation when exposed to certain stimuli. Correa et al. (2015) transformed the concept of multi-material lamination with wood to the field of 3D printing through the interwoven use of Acrylonitrile Butadiene Styrene (ABS) with wood. El-Dabaa et al. (2021a) investigated the translation of the different grain orientations in natural wood to the 3D printing of different layer directions. Other 3D printing parameters for wooden composites have been studied, such as layer height, inter-filament distance, and the ratio between active and passive layers (Le Duigou et al. 2021), in addition to the number of layers and the filling ratio setting in 3D printing. This ratio controls porosity and water permeability in 3D printed wood, therefore mimicking the difference in compactness ratio of wooden fibres in different types of natural wood (Tahouni et al. 2021). Similar to the effect of the type of wood on deflection value in natural wood, the dimensional change causing shape-shifting in 3D printed wooden composites is affected by the ratio of wooden particles to Polylactic Acid (PLA) (Tomec et al. 2021).

Lamination with passive layers is not only studied in terms of layer type, but also the percentage and location of the layer. These design-controlled parameters affect the motion response behaviour of the wooden sample. Laminating specific parts of the wooden sample with a passive layer has been studied to allow for the composite to act as a hinge, while controlling the location of the lamination part affects the type of motion (El-Dabaa et al. 2020, 2021b). Table 4 shows that the lamination of hygromorphic material using natural wood has been addressed in more studies than 3D printed wood.

Tracking and evaluation methods for hygroscopic design behaviour

The effect of hygroscopic properties has been studied in relation to several aspects involving motion response such as the angle of curvature, response time, sustainability, aesthetics, and texture (Holstov et al. 2015b), in addition to actuation capacity, or the force produced by the response, the structural ability regarding applied loads, and durability, or resistance to degradation (Holstov et al. 2017).

The tracking and evaluation of hygromorphic-based composites are generally discussed in the literature based on two main methods: (1) manual laboratory testing and (2) computational methods. Manual laboratory testing typically requires callipers and timers to take sequential readings of different material motion responses such as deflection values or distances. Manual laboratory testing also requires the use of environmental sealed chambers, humidifiers, dehumidifiers and controlled water spraying mechanisms. Computational methods on the other hand use approaches such as image analysis to evaluate motion response, in addition to

Table 4 Studies that involve different fabrication methods for hygromorphic adaptive facades

Fabrication methods	References
3D printing and robotics	Correa et al. (2015), Vazquez and Gursoy (2020), El-Dabaa and Salem (2021), Cheng et al. (2021), El-Dabaa et al. (2021a), Tahouni et al. (2021), Ibrahim et al. (2022a, b)
Lamination	Reichert et al. (2015), Rüggeberg and Burgert (2015), Holstov et al. (2015b, 2017), Dierichs and Menges (2016), Vailati et al. (2017, 2018a, b), Wood et al. (2018), Abdelmohsen et al. (2018, 2019a, b, c), Augustin and Correa (2019), El-Dabaa and Abdelmohsen (2019), Pelliccia et al. (2020), Grönquist et al. (2020), El-Dabaa et al. (2020, 2021b), Nan et al. (2020), Aly et al. (2021), Ibrahim et al. (2022b)

numerical modelling methods to compute and predict motion responses (Vailati et al. 2018a; Abdelmohsen et al. 2018, 2019a).

It was shown that several parameters affect the motion and morphology of wood when exposed to increase in humidity. Thus, fabrication methods and wood morphology configurations are affected by these hygroscopic design parameters. The idea of encoding programmable materials is based on several material parameters that control their motion response, therefore affecting the hygroscopic variables leading to passive motion response when exposed to variation in humidity levels. The encoding of passive motion response requires a deep understanding of not only the effect of each parameter but also the ability to acquire similar motion responses through various combinations of these parameters. Based on this idea, El-Dabaa and Abdelmohsen (2022a, b) developed a computational shape-shifting grammar to control and program the utilization of hygromorphic materials in adaptive façade design from a generative design perspective through tracing the multiple combinations and permutations of different embedded and controlled parameters. The backend matrix of this shape-shifting grammar is shown in Fig. 2.

This shape-shifting grammar reveals the output motion response for material configuration through a series of records. The variables in this grammar represent embedded and controlled hygroscopic parameters. For example, a controlled design parameter such as isolating a specific percentage of a single or opposite sides of the wooden sample shows that the output results named "tokens" in the computational form are resembled by deflection value and type of motion. Relating and combining the variables with the records reveal semantic rules for each material configuration (El-Dabaa and Abdelmohsen 2022a).

Hygroscopic motion response has been studied through different methodologies such as numerical studies, simulation, and wood motion morphologies and grammars (El-Dabaa and Abdelmohsen 2018, 2022a), in addition to computational design using flex sensors and simulation, where the pressure on flex sensors that are added in between wooden laminated layers is used to derive the angle of curvature of laminated samples (Abdelmohsen et al. 2018). Accordingly, working on the physical experimental approach is a time-consuming, cost and labour-intensive process. Working on numerical and simulation approaches that simulate physics and material properties however allows for studying various parameters. Although several studies have attempted to program adaptive structures using hygroscopic properties, there seems to be a gap in relating the physical interface of the material as a real-time motion response to the computational interface as motion analysis in relation to their encoded parameters.

Material programmability requires physical and numerical experiments to study the effect of each hygroscopic design parameter on its passive response behaviour to humidity. Several institutions and laboratories have studied programmable materials and the effect of hygroscopic design variables as a passive responsive mechanism using several methods, as shown in Table 5, such as the Institute for Computational Design (ICD) at the University of Stuttgart (Reichert et al. 2015), and the Self-Assembly Lab (SAL) at MIT (Tibbits and Cheung 2012). Table 5 also shows the tested parameters such as the deflection value of wooden samples and speed response. The literature tends to test the deflection value through either angle of curvature or radius.

Implementing hygroscopic properties in architectural adaptive structures

Hygromorphic design has been implemented in architectural adaptive façades to respond to variations in surrounding stimuli. The process of selecting programmable materials in hygromorphic composites for implementation in the design of these façades depends on several factors to control their motion response, including but not limited to responsiveness, response speed and curvature, actuation capacity through magnitude and response of geometric variations, structural resistance, durability, sustainability and aesthetics (Holstov et al. 2017). Table 6 provides an overview of studies that involve the different facets of implementation of hygroscopic properties in architectural adaptive façades, including: (1) performative aspects, such as percentage of openings, air flow, durability, and wood motion (this includes the motion response behaviour of prototypes studied); (2) adaptive solutions, including adaptive façades, responsive structures, and responsive shading, textiles; and (3) upscaling-related aspects, including patterns, variation in thicknesses and joint design.

Based on the dimensions identified earlier, we demonstrate below the state of the art in hygromorphic programmability in architectural applications and adaptive skins. Eight architectural applications were selected, as shown in Table 7, where "Responsiveness" refers to the type of external stimulus (humidity or temperature). "Programmability parameters" refers to decoding the hygroscopic parameters of the materials

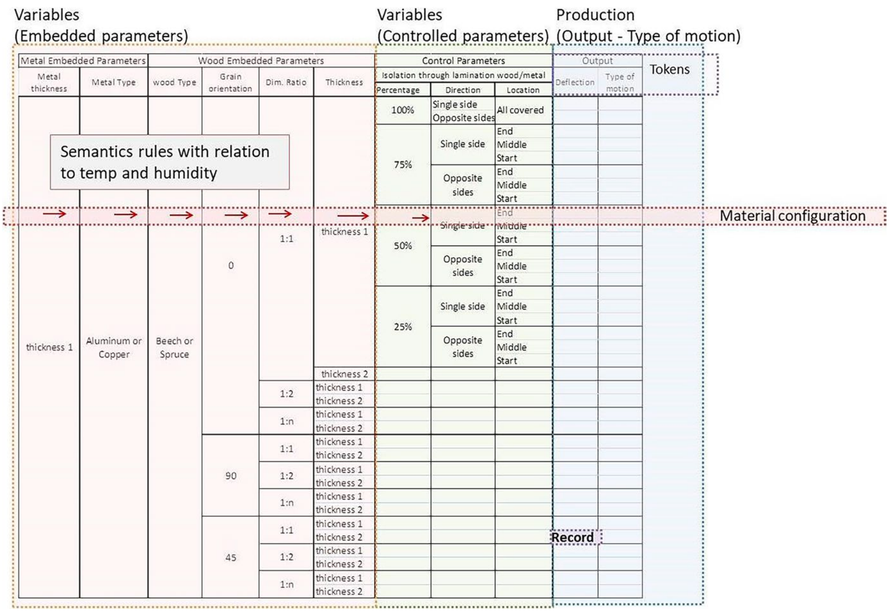


Fig. 2 Computational shape-shifting grammar backend matrix (El-Dabaa and Abdelmohsen 2022a)

in each application in order to develop the necessary morphological grammars for adaptive systems. "Fabrication methods" refers to the methods used to program materials, such as wet/dry lamination and 3D printing techniques. "Performance Aspects" refers to the main aim of the adaptive system; for example, regulating daylight in space, reducing energy consumption, robotic motion, etc. "Adaptive Solution" refers to the type of implementation of hygromorphic design in architectural design; for example, adaptive façades, responsive structures, etc. Finally, "Upscaling" refers to the strategies used in upscaling small-scale hygromorphic prototypes in terms of unit repetition, grooving, overlap, etc.

Table 5 Classification of studies that address tracking and evaluation methods and their tested parameters in architectural adaptive façades

Analysis aspects	References
Tracking and evaluation methods	Numerical simulation Rüggeberg and Burgert (2015), Dierichs and Menges (2016), Arends et al. (2017), Abdelmohsen et al. (2018, 2019a), Vailati et al. (2018a), Grönquist et al. (2018), Augustin and Correa (2019), Grönquist et al. (2020), El-Dabaa et al. (2021b), Aly et al. (2021), El-Dabaa and Abdelmohsen (2022a)
	Physical experiments Correa et al. (2015), Reichert et al. (2015), Rüggeberg and Burgert (2015), Dierichs and Menges (2016), Arends et al. (2017), Dierichs et al. (2017), Holstov et al. (2017), Le Duigou and Castro (2017), Vailati et al. (2017, 2018a, b), Wood et al. (2018), Grönquist et al. (2018), Abdelmohsen et al. (2018, 2019a, b, c), Anis (2019), Augustin and Correa (2019), El-Dabaa and Abdelmohsen (2019), Giachini et al. (2020), Holstov et al. (2015a, b), Ibrahim et al. (2020, 2022a, b), Pelliccia et al. (2020), Nan et al. (2020), Vazquez and Gursoy (2020), Aly et al. (2021), Cheng et al. (2021), El-Dabaa et al. (2021b), Le Duigou et al. (2021), Tahouni et al. (2021), Tomec et al. (2021), El-Dabaa and Abdelmohsen (2022a)
	Computational grammars El-Dabaa and Abdelmohsen (2018), El-Dabaa et al. (2020), El-Dabaa and Abdelmohsen (2022a, b)
Tested parameters	Deflection (angle of curvature, radius) Rüggeberg and Burgert (2015), Le Duigou and Castro (2017), Vailati et al. (2017, 2018a, b), Grönquist et al. (2018), Wood et al. (2018), Abdelmohsen et al. (2018, 2019b, c), Anis (2019), El-Dabaa and Abdelmohsen (2019), Ibrahim et al. (2020), Pelliccia et al. (2020), El-Dabaa et al. (2020, 2021a, b), Nan et al. (2020), Aly et al. (2021), El-Dabaa and Abdelmohsen (2022a, b), Ibrahim et al. (2022a, b)
	Response speed Rüggeberg and Burgert (2015), Le Duigou and Castro (2017) Abdelmohsen et al. (2018, 2019b, c) (Ibrahim et al. 2020) Pelliccia et al. (2020)
	Stored elastic energy/axial stress
	Grönquist et al. (2018)
	Moisture content
	Vailati et al. (2017)

Discussion

This section identifies the findings from the review and highlights the main gaps in the literature. The implementation of hygroscopic behaviour of wood in the architectural realm has successfully introduced a new passive motion technique with zero-energy consumption. Studies under investigation in this paper have explored the ability to control and programme hygroscopic response behaviour in adaptive architectural façades through both physical and numerical methods. Findings from the review have demonstrated the following gaps and potentials.

Potentials of bi-material manufacturing mechanism

The wooden bilayer mechanism indicates the manufacturing method for merging two layers with different properties that vary in their expansion coefficients when exposed to external stimuli, thus causing passive motion response. Controlling the bilayer manufacturing mechanism of hygroscopic-based materials takes place to programme several motion responses, speed, and deflection values. This bilayer manufacturing mechanism can be divided in wood into lamination and 3D- printing.

Lamination

The literature shows various lamination-based studies that affect the response behaviour of hygroscopic design. Lamination has been studied based on several factors including the difference in the type of layers, thickness, grain orientation and lamination patterns. It was observed that most of the studies that involve lamination focus on wooden passive layers, while other materials being laminated to wood are investigated such as metals (El-Dabaa and Abdelmohsen 2019; El-Dabaa et al. 2020), silica gel (Aly et al. 2021), fabric glass (Holstov et al. 2017), and nylon (Augustin and Correa 2019) to control the motion response or add a property for wood to be stimulated by other stimuli. This variation allows for programming the stimulus control of the material rather than relying solely on humidity as the primary stimulus, leading to a wide range of potential motion configurations.

It was also observed that laminating samples with different thicknesses affect both speed response and angle of curvature. Thick samples tend to have less curvature with a slow speed response. The response behaviour of the laminated layer varies according to the thickness ratio between the active and passive layers (Holstov et al. 2015b; Rüggeberg and Burgert 2015; Vailati et al. 2017, 2018b; Wood et al. 2018; Grönquist et al. 2018; El-Dabaa and Abdelmohsen 2019; Pelliccia et al. 2020; El-Dabaa et al. 2020).

Using grain orientation as a lamination design driver was seen to allow for controlling speed response, direction and value of curvature. Angular grain orientation was observed to result in a twisting motion response (Reichert et al. 2015; Holstov et al. 2015b; Wood et al. 2018; Abdelmohsen et al. 2019a, b, c; El-Dabaa and Abdelmohsen 2019; Anis 2019; Pelliccia et al. 2020; El-Dabaa et al. 2020; Nan et al. 2020). Samples

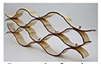
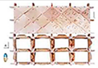
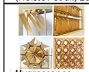
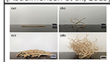
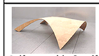
Table 6 Classification of studies that involve different facets of implementing hygroscopic properties in architectural adaptive façades, including performative aspects, adaptive solutions, and upscaling

Implementation of hygroscopic properties	References
Performative aspects	Percentage of openings and daylighting Reichert et al. (2015), Holstov et al. (2015b, 2017), Vailati et al. (2018b), Abdelmohsen et al. (2019b), Anis (2019), El-Dabaa et al. (2021b)
	Air flow Augustin and Correa (2019), Anis (2019), Pelliccia et al. (2020)
	Aesthetic (visual impact and effect over time)
	Holstov et al. (2017)
	Durability of response (number of cycles and programmability of hygroscopic motion response) Reichert et al. (2015), Rüggeberg and Burgert (2015), Holstov et al. (2015b, 2017), Vailati et al. (2017, 2018a), Wood et al. (2018), Abdelmohsen et al. (2019c)
	Motion Reichert et al. (2015), Dierichs and Menges (2016), Holstov et al. (2017), Wood et al. (2018), Abdelmohsen et al. (2018, 2019a, 2019b, 2019c), Anis (2019), Ibrahim et al. (2020, 2022a, 2022b), Grönquist et al. (2020), El-Dabaa et al. (2020), Nan et al. (2020), Aly et al. (2021)
Adaptive solutions	Adaptive facades Reichert et al. (2015), Holstov et al. (2015b, 2017), Abdelmohsen et al. (2019a, 2019b), El-Dabaa and Abdelmohsen (2019, 2022a), Anis (2019), Pelliccia et al. (2020), El-Dabaa et al. (2020, 2021b), Nan et al. (2020), Aly et al. (2021), Ibrahim et al. (2022a)
	Responsive structures Holstov et al. (2015b), Rüggeberg and Burgert (2015), Dierichs and Menges (2016), Holstov et al. (2017), Dierichs et al. (2017), Wood et al. (2018), Grönquist et al. (2020)
	Responsive shading Vailati et al. (2018b)

Table 6 (continued)

Implementation of hygroscopic properties		References
Upscaling	Patterns	Repetition Reichert et al. (2015), Holstov et al. (2015b), Dierichs and Menges (2016), Holstov et al. (2017), Abdelmohsen et al. (2019b), Augustin and Correa (2019), Anis (2019), Pelliccia et al. (2020), Aly et al. (2021), El-Dabaa et al. (2021b), Ibrahim et al. (2022a)
		Overlapping Reichert et al. (2015), Abdelmohsen et al. (2019b), Vailati et al. (2018b), Grönquist et al. (2020)
	Thickness variation	Grooving/milling Vailati et al. (2017, 2018a)
	Joint design	Interlocking joints Wood et al. (2018), Nan et al. (2020)

Table 7 Evaluating the hygroscopic programmability of selected architectural adaptive projects

	Responsiveness			Programmability parameters									Fabrication methods		Performative Aspects					Adaptive solution			Upscaling		
	Moisture Activation	Temperature	Temp. & Humidity	Direction wood cut	Type of wood	Grain Orientation	Passive layer	Thickness	Dimensional Ratio	Geometrical configurations	Perforations	Moisture Content	3D Printing	Lamination	Percentage of opening & daylight	Air flow	Aesthetic	Durability	Motion	Adaptive facades	Responsive structure	Responsive shading	Patterns	Thickness variation	Joint design
 **"HygroSkin"** (Reichert et al., 2015)	x					x	x	x	x					x	x	x		x	x	x			x		
 **"HygroScope"** (Reichert et al., 2015)	x					x	x			x		x		x	x	x			x		x		x		
 **Responsive facade** (Nan et al., 2020)	x					x	x			x		x		x	x	x			x	x					x
 **Responsive umbrella** (Holstov et al., 2015)	x					x	x			x		x		x	x	x			x			x	x		
 **Responsive facade** (Holstov et al., 2017)	x					x	x			x		x		x	x	x			x	x			x		
 **Hygroscapes** (Abdelmohsen et al., 2019)	x					x	x		x	x		x		x	x				x	x			x		
 **Granular pavilion** (Dierichs & Menges, 2016)	x					x	x		x	x		x		x					x		x		x		
 **Self-assembly & self rigidizing structures** (Wood et al., 2016)	x			x		x	x	x	x	x		x		x					x		x		x		x

with grain orientation parallel to the long axis of the material had slower curvature than those with grain orientation perpendicular to the long axis.

Several lamination patterns were identified, resulting from both the gluing mechanism, including gluing, mechanical fixation, spot gluing and direct lamination (Holstov et al. 2017) and the layering pattern itself, including milling grooves and perforations. These were observed to control the speed response and deflection value of the material when exposed to external stimuli (Vailati et al. 2017, 2018a). The limitation in studying lamination however lies in the wide range of discrepancies that occur due to the natural formation of wooden samples, which in turn slightly affects the consistency and accuracy of the data and readings.

Wood 3D printing

Generally, the 3D printing of wooden-based composites has different lamination parameters, but with a similar essence to that of natural wood. These parameters include the number of printed layers and infill height (El-Dabaa et al. 2020, 2021a), the percentage of wooden particles to PLA (Tomec et al. 2021; El-Dabaa et al. 2021a), the infill percentage (Tahouni et al. 2021), and the inter-filament distance, and ratio between active and passive layers (Le Duigou et al. 2021). 3D printing introduces novel patterns and design configurations (Ibrahim et al. 2022a). The limitation lies however in the ratio of wooden particles to PLA in filament rolls, as the final composite is not a 100% wooden composite as is the case with natural wood.

Upscaling

The upscaling of hygroscopic-based materials for large-scale applications is still a topic under study, for both natural wood and 3D printing. The main challenge in upscaling lies in the aspect ratio of the sample including length, width and depth. Increasing the ratio of the sample affects the depth, thus reducing its response behaviour and speed. Although several strategies have been developed that involve grooving and interlocking joints, this aspect is still identified as a gap in the implementation of hygroscopic design in adaptive architecture. Research on upscaling of hygroscopic-based materials allows for the potential full-scale implementation on building facades. However, durability is a significant factor that still requires further investigation in long durations to be able to identify the potential parameters needed to enhance durability in terms of both visual appearance and performance.

Computational interface

The process of testing and simulation of hygroscopic design parameters in a digital platform can potentially save time and cost in comparison to physical tests. Several computational approaches have been introduced, including non-linear spring-based simulation models (SSM), which simulate the response behaviour of material expansion. This requires three-dimensional types of springs that represent the three main directions of wooden cuts (radial, tangential and longitudinal). The expansion coefficient of these directions along with wood types can be inserted into the model, thus allowing for the simulation of wood behaviour for different geometries, thicknesses and grain orientations (Reichert et al. 2015). Other attempts have linked the hygroscopic physical interface to a computational interface through flex sensors. The sensor is connected to a script that translates the physical pressure on a given wooden sample to angles of curvature in real time (Abdelmohsen et al. 2018). A non-linear solid mechanics approach has also been implemented to simulate the linear elastic and anisotropic response of the hygroscopic swelling behaviour through parametric simulations using COMSOL Structural Mechanics Module as finite element modelling (Abdelmohsen et al. 2019a).

Other approaches have developed a systematic process to derive motion grammars for hygroscopic response behaviour when exposed to external stimuli to allow for controlling and tracking motion (El-Dabaa and Abdelmohsen 2018, 2022a; El-Dabaa et al. 2020). Further research is needed to develop computational frameworks that take into consideration findings from physical experiments and the associated parameters to simulate specifically the upscaling process of the material, deflection value, speed and durability.

Conclusion and future directions

This paper presents a systematic review of the state of the art of utilizing hygroscopic properties of wood in architectural adaptive facades. The integration of hygroscopic design in adaptive architecture has been generally studied as a zero-energy consumption motion mechanism and an alternative approach to high-tech high-cost mechanical actuators. This field of research is still in the experimental phase. The paper highlights potential research gaps and topics for consideration in future research.

The paper introduced the current state of the process of programming motion responses of wood based on three main dimensions: (1) hygroscopic design parameters, (2) analysis methods and computational approaches, and (3) the implementation of hygroscopic design, as seen in adaptive architecture precedents that utilize hygromorphic-based materials and have been built since 2010.

These applications were evaluated based on aspects related to responsiveness, programmability parameters, fabrication methods, functional analysis, adaptive solutions, and upscaling. The paper concludes with an identification of potential areas for further research and development, with a specific focus on lamination, upscaling and computational interfaces.

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Author contributions RD and SA worked on developing the structure and method of the paper and contributed to the manuscript writing. All authors reviewed the manuscript.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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